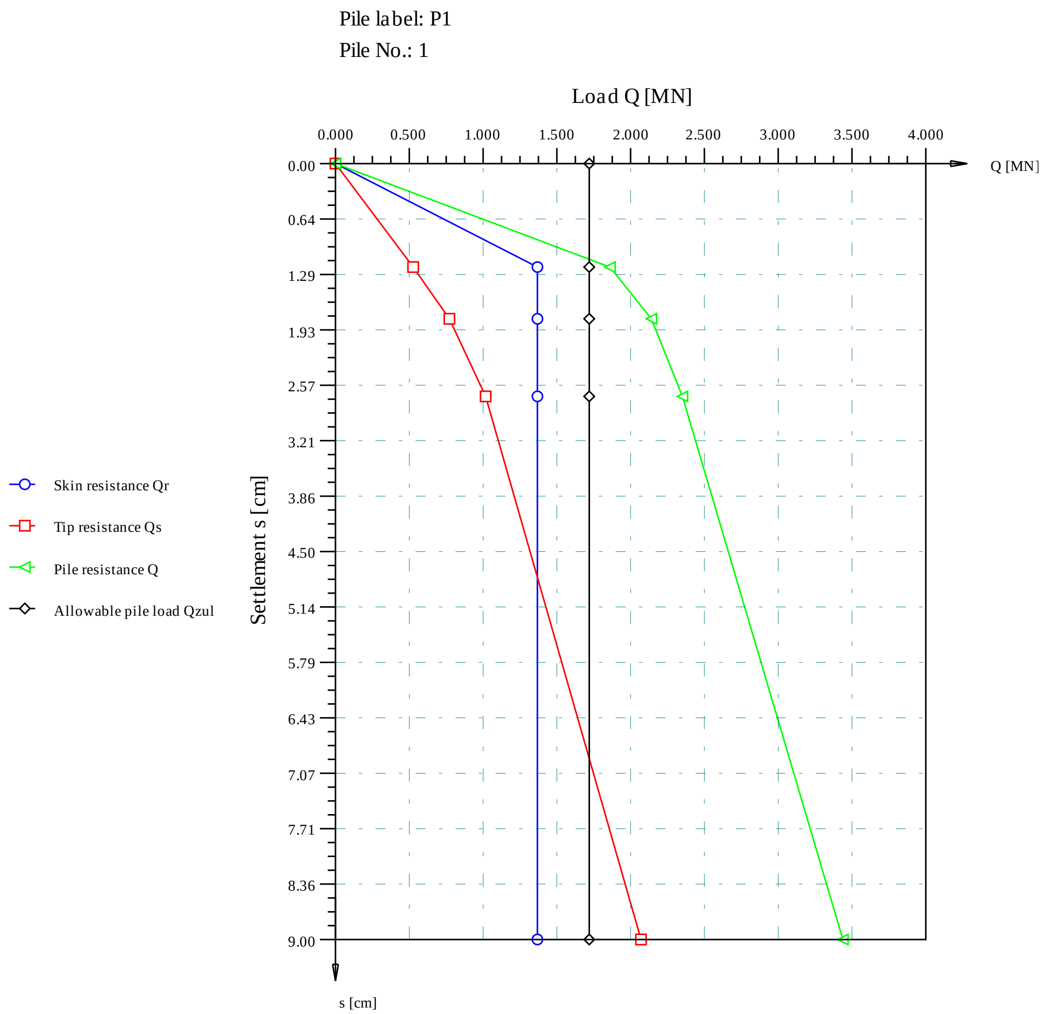
Bearing Capacity of Single Pile or Pile Wall by the Program *GEO Tools*



Load settlement curve of pile according to DIN 4014

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2022

Content

1 Bearing Capacity of Single Pile or Pile wall

1.1 Introduction

Various problems in geotechnical Engineering can be investigated by the program *GEO Tools*. The original version of the program *GEO Tools* in *GEOTEC Office* was developed by Prof. M. Kany, Prof. M. El Gendy and Dr. A. El Gendy to calculate the settlement and bearing capacity of single pile or pile wall according to DIN 4014 (edition 03/1990) and to draw the results in diagrams according to the German Code.

After the death of Prof. Kany, Prof. M. El Gendy and Dr. A. El Gendy further developed the program to meet the needs of practice. The development includes the interpolation between the values of Tables 1, 2, 4 and 5 of the German standard DIN 4014. User friendly interface for defining data or present results is also developed. Furthermore, many changes were carried out to the graphical output.

1.2 Building the program

By the program *GEO Tools*, it can be presented graphically the curve of the pile resistance *Q*(*s*) as a function of the pile head settlement *s* according to Figure 1 and B2 in DIN 4014 (see the numerical examples at the end of the book).

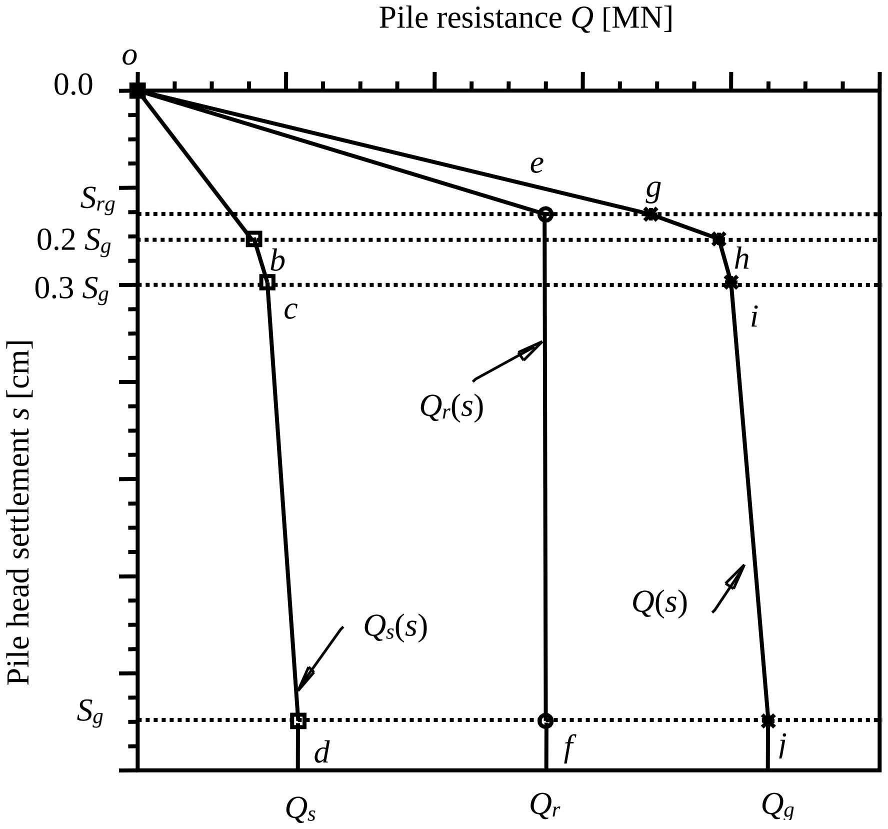


Figure 1 Construction of the resistance line using the tables 1 to 6

The load bearing capacity and settlement of single piles and pile walls can be determined and graphically displayed according to DIN 4014 by the program *GEO Tools*.

When defining the project data in the program, the calculation task must first be selected between:

- Single pile or Pile wall -

For single piles, the pile tip resistance and then the friction on the pile shaft are examined. In the case of pile walls, the geometrical data of the wall are also required.

1.3 Bearing capacity of single pile according to DIN 4014

First, the characteristic values for the zone under the pile tip are defined, when determining the bearing capacity of the single pile.

There are three possibilities for defining the three tip resistance values σ (pile tip resistance):

- direct definition of σ, σ_1 and σ_{gr}

- defining the cone resistance q_s (for non-cohesive soils) and interpolation in the Table 1 in DIN 4014 (see Table 1)

- defining the shear strength c_u of the undrained soil and interpolation in the Table 2 in DIN 4014 (see Table 2).

Table 1 Tip resistance σ_s [MN/m²] in non-cohesive soil as a function of relative settlement, *s*/*D* or s/D_F, and average penetrometer tip resistance (according to DIN 4014, Table 1)

Relative settlement of the pile head *s*/*D* or s/D_F	Tip resistance σ_s MN/m² *)			
	Average penetrometer tip resistance q_s [MN/m²]			
	10	15	20	25
0,02	0,7	1,05	1,4	1,75
0,03	0,9	1,35	1,8	2,25
0,10 = s_g	2,0	3,0	3,5	4,0

*) Intermediate values may be linearly interpolated.
For bored piles with enlarged base the values shall be reduced to 75 %.

Table 2 Tip resistance σ_s [MN/m^2] in cohesive soil as a function of relative settlement, s/D or s/D_F, and undrained shear strength c_u [MN/m^2] (according to DIN 4014, Table 2)

Relative settlement of the pile head s/D or s/D_F	Tip resistance σ_s MN/m^2 *)		
	Undrained shear strength c_u [MN/m^2]		
	0,1	0,2	0,4
0,02	0,35	0,9	2,0
0,03	0,45	1,1	2,4
0,10 = s_g	0,8	1,5	2,9
Intermediate values may be linearly interpolated. For bored piles with a flared base the values are reduced to 75 %.			

Where friction can influence the sounding results obtained with a DPH type penetrometer, SPT type penetrometer as specified in DIN 4094 should be used. See Table 3 for conversion of results.

Table 3 Conversion factor q_s/N_{30} for standard penetrometer (according to DIN 4014, Table 3)

Type of soil	q_s/N_{30}
Fine to medium or slightly silty sand	0,3 to 0,4
Sand or slightly gravelly sand	0,5 to 0,6
Gap-graded sand	0,5 to 1,0
Sandy gravel or gravel	0,8 to 1,0

There are also three possibilities for defining the input data required for skin friction for each layer:

- direct definition of ultimate limit state value τ_{mf} of pile skin friction
- defining the cone resistance q_s (for non-cohesive soils) and interpolation in the Table 4 in DIN 4014 (see Table 4)
- defining the shear strength c_u of the undrained soil and interpolation in the Table 5 in DIN 4014 (see Table 5).

Table 4 Ultimate skin friction resistance τ_{mf} for bored piles in non-cohesive soils (according to DIN 4014, Table 4)

Mean CPT cone resistance q_s MN/m^2	Ultimate skin friction resistance τ_{mf} MN/m^2 *)
0	0
5	0,04
10	0,08
∃ 15	0,12

*) Intermediate values may be linearly interpolated.

Table 5 Ultimate skin friction resistance τ_{mf} for bored piles in cohesive soils (according to DIN 4014, Table 5)

Undrained shear strength c_u [MN/m^2]	Ultimate skin friction resistance τ_{mf} MN/m^2 *)
0,025	0,025
0,1	0,04
∃ 0,2	0,06

*) Intermediate values may be linearly interpolated.

1.4 Bearing capacity of pile wall (diaphragm wall)

1.4.1 Introduction

The determination of bearing capacity of pile walls is carried out according to DIN 4014 essentially with the same formulas and tables as for single piles. However, reduction factors in the pile tip resistance are necessary, as explained below:

1.4.2 Reduction factor

When determining the load capacity of diaphragm wall panels, the ultimate skin friction resistance shall be as specified in Table 4 and Table 5, and the tip resistance, as specified in Table 1 and Table 2) using a reduction factor, ν, as indicated in Table 6.

Table 6 Reduction factor ν for tip resistance σ_s of diagram wall (according to DIN 4014, Table 6)

Length to thickness ratio *)	1	∃ 5
ν	1	0,6
*) Intermediate values may be linearly interpolated.		

1.5 Bearing capacity of single pile according to EA-Piles

1.5.1 General

(1) The elements of the characteristic resistance-settlement curve for bored piles are shown in Figure 2 for settlement up to $s_{ult} = s_g$.

(2) The settlement-dependent pile base resistance $R_b(s)$ and the pile shaft resistance $R_s(s)$ are differentiated.

(3) The limit settlement for $R_{b,k}$ ($s_{ult} = s_g$) is:

$s_g = 0,10 \times D_b$

where:

D_b diameter of the pile base in [m].

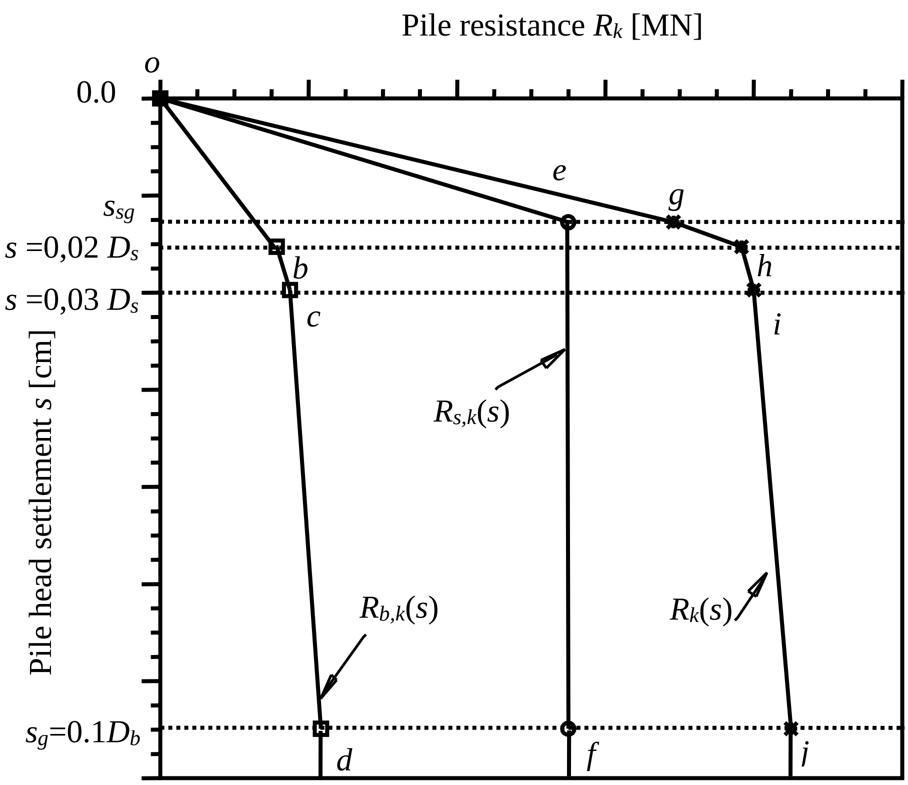


Figure 2 Elements of the characteristic resistance-settlement curve for bored piles

(4) The governing reference variable for settlement in the serviceability limit state is the pile shaft diameter D_s. On piles without an enlarged base the pile diameter D (here: $D = D_s = D_b$) is adopted as the reference variable for settlement at the ultimate limit state. The pile diameter D_b is the governing reference variable for piles with an enlarged base. The diaphragm wall thickness D shall be adopted for diaphragm wall elements barrettes).

(5) The limit settlement applies for the characteristic pile shaft resistance $R_{s,k}(s_{sg})$ in [MN] in at ultimate limit state:

$$s_{sg} \text{ [cm]} = 0{,}5 \times R_{s,k}\,(s_{sg}) \text{ [MN]} + 0{,}5 \text{ [cm]} \leq 3 \text{ [cm]}$$

(6) The characteristic axial pile resistance is determined from

$$R_{k(s)} = R_{b,k(s)} + R_{s,k(s)} = q_{b,k} \times A_b + \sum A_{qs,k,i} \times A_{s,i}$$

where:

A_b	nominal value of the pile base area;
$A_{s,i}$	nominal value of the pile shaft area in stratum *i*;
$q_{b,k}$	characteristic value of the base resistance, derived from Table 7 and Table 9 (according EA-Piles, Table 5.12 and 5.14) ;
$q_{s,k,i}$	characteristic value of the skin friction in stratum *i*, derived from Table 8 and Table 10 (according to EA- Piles, Table 5.13 and 5.15);
$R_{c,k(s)}$	settlement-dependent, characteristic compressive pile resistance;
$R_{b,k(s)}$	settlement-dependent, characteristic base resistance;
$R_{s,k(s)}$	settlement-dependent, characteristic shaft resistance; s_{sg} limit settlement for the settlement-dependent characteristic shaft resistance.

1.5.2 Empirical values of base resistance and skin friction

(1) The empirical data for pile base resistance and skin friction given in Table 7 to Table 9Table 10 (according to EA-Piles, Table 5.12 to Table 5.15) apply to bored piles from D_s or D_b = 0,30 to 3,00 [m], which embed at least 2,50 [m] into a load-bearing stratum and depend on:

- the mean cone resistance q_c of the CPT with depth in non-cohesive soil and
- the shear strength of the undrained soil $c_{u,k}$ for cohesive soils.

Note: The magnitude of the lower table values (minimum values) were first adopted in DIN 4014:1990-03 on the basis of the investigations by [4].

(2) Condition for the application of the values of Table 7 and Table 9 (according to EA-Piles, Tables 5.12 and 5.14) are:

– the thickness of the load-bearing layer below the pile base is not less than 3 times the pile base diameter, but at least 1,50 [m] and

– $q_c \geq 7{,}5$ [MN/m²] or $c_{u,k} \geq 100$ [kN/m²] is confirmed in this zone.

Regardless of this, founding the pile bases in zones where $q_c \geq 10$ [MN/m²] is recommended.

Table 7 Empirical data ranges for the characteristic base resistance $q_{b,k}$ for bored piles in non-cohesive soils (according to EA-Piles, Table 5,12)

Relative settlement of the pile head s/Ds or s/D_b	Pile base resistance $q_{b,k}$ [kN/m²]		
	mean CPT cone resistance q_c [MN/m²]		
	7,5	15	25
0,02	550–800	1 050–1 400	1 750–2 300
0,03	700–1 050	1 350–1 800	2 250–2 950
0,10 = s_g	1 600–2 300	3 000–4 000	4 000–5 300
Intermediate values may be linearly interpolated. For bored piles with enlarged base the values shall be reduced to 75 %.			

Table 8 Empirical data ranges for the characteristic skin friction $q_{s,k}$ for bored piles in non-cohesive soils (according to EA-Piles, Table 5.13)

Mean CPT cone resistance q_c [MN/m²]	Ultimate limit state value $q_{s,k}$ of pile skin friction [kN/m²]
7,5	55–80
15	105–140
∃ 25	130–170
Intermediate values may be linearly interpolated.	

Table 9 Empirical data ranges for the characteristic base resistance $q_{b,k}$ for bored piles in cohesive soils
(according to EA-Piles, Table 5.14)

Relative settlement of the pile head s/D_s or s/D_b	Pile base resistance $q_{b,k}$ [kN/m²]		
	Shear strength $c_{u,k}$ of the undrained soil [kN/m²]		
	100	150	250
0,02	350–450	600–750	950–1 200
0,03	450–550	700–900	1.200–1 450
0,10 = s_g	800–1 000	1 200–1 500	1 600–2 000
Intermediate values may be linearly interpolated. For bored piles with a flared base the values are reduced to 75 %.			

Table 10 Empirical data ranges for the characteristic skin friction $q_{s,k}$ for bored piles in cohesive soils
(according to EA-Piles, Table 5.15)

Shear strength $c_{u,k}$ of the undrained soil [kN/m²]	Ultimate limit state value $q_{s,k}$ of pile skin friction [kN/m²]
60	30–40
150	50–65
≥ 250	65–85
Intermediate values may be linearly interpolated.	

1.6 Defining the project data

1.6.1 Firm Header

When printing the results, the main data (firm name) are displayed on each page at the top in two lines. Firm name can be defined, modified and saved using the "Firm Header" option from the setting tab (see Figure 3).

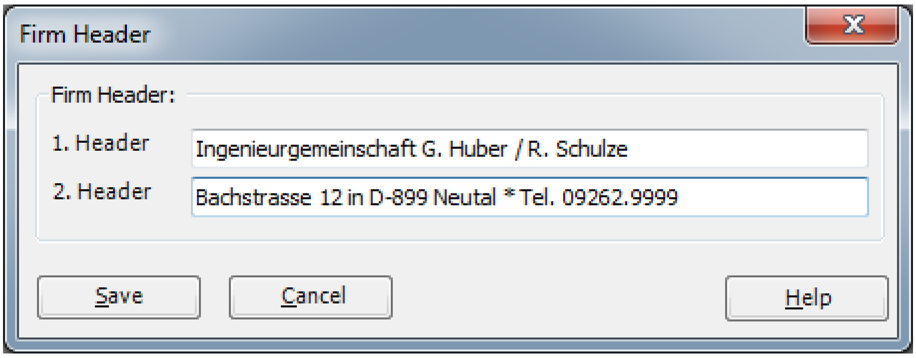


Figure 3 Firm Header

1.6.2 Task of the program *GEO Tools* (Analysis Type)

The program *GEO Tools* can be used to analyze various problems in Geotechnical Engineering for shallow foundations and deep foundations, Figure 4.

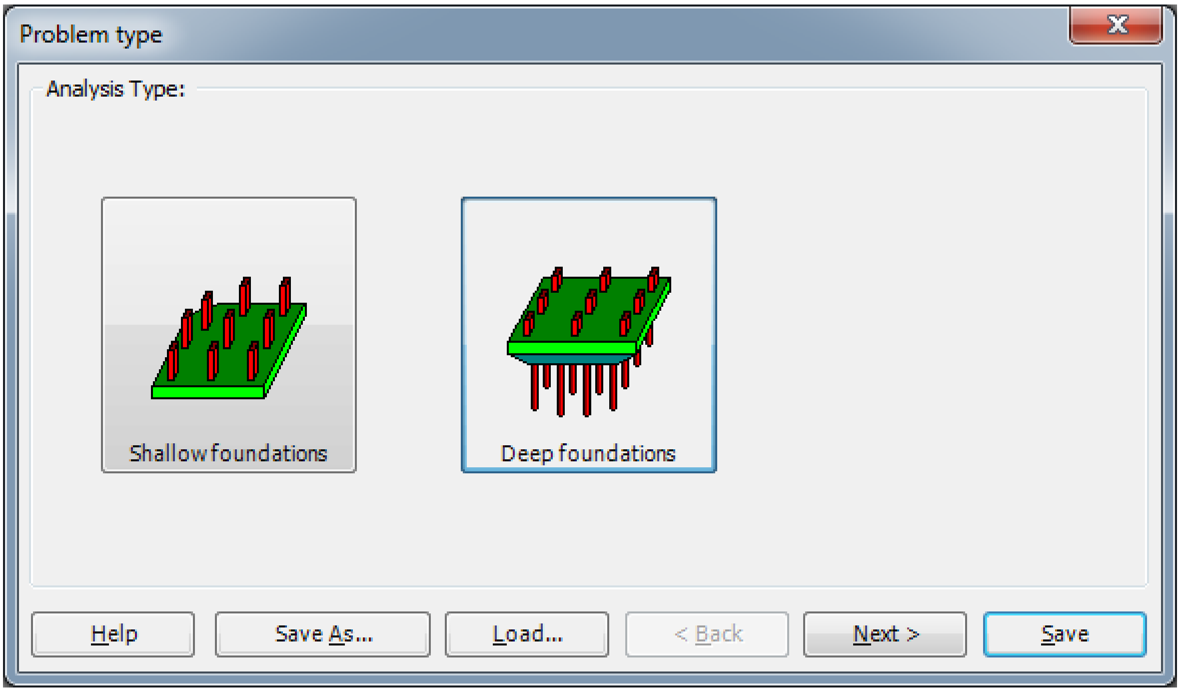


Figure 4 Problem type

According to the main menu (Figure 5) the following geotechnical problems can be calculated for deep foundations:

- Analysis of single pile
- Bearing capacity and settlement of single pile or pile wall
- Analysis of piled raft
- Stress coefficients according to GEDDES
- Sheet pile wall
- Analysis of single barrette

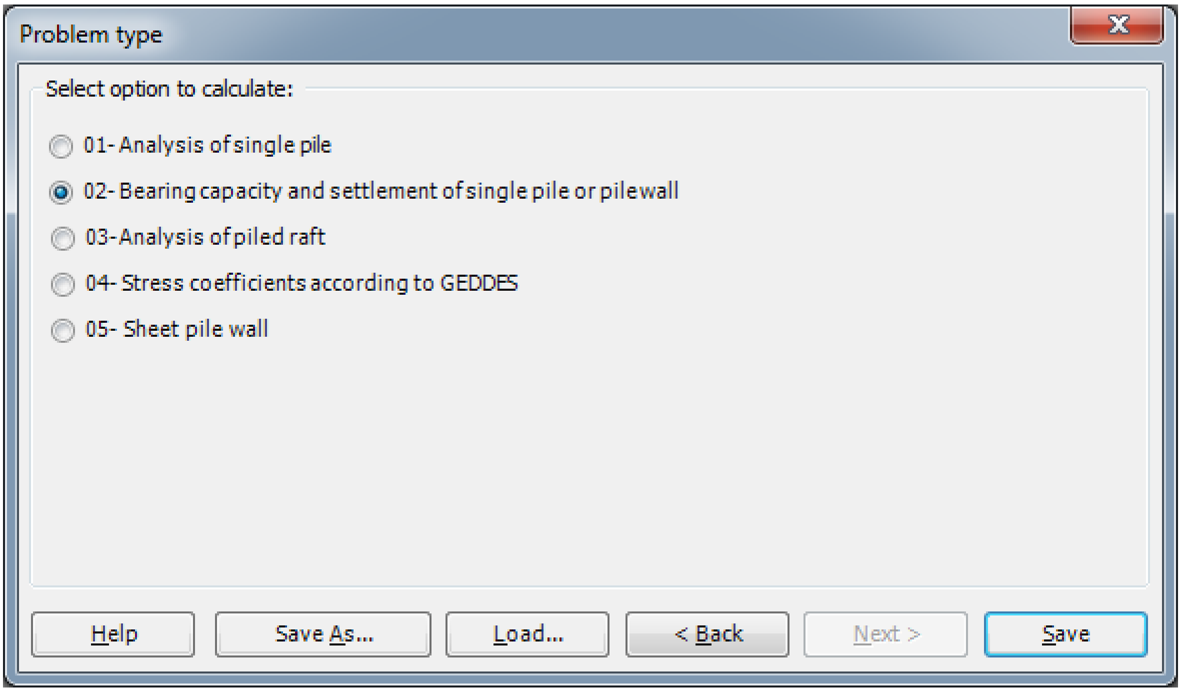


Figure 5 Problem type for deep foundation

In menu of Figure 5 select the option:

- Bearing capacity and settlement of single pile or pile wall

The following paragraph describes how to determine the load bearing capacity and the settlement of single piles and pile walls by the program *GEO Tools*. The bearing capacities and settlements of single bored piles or bored pile walls according to DIN 4014 or EA piles can be determined. The input data are the dimensions of the piles, the tip resistance from *CPT* cone resistance tests q_c or the shear strength c_u of the soil layers. The Ultimate skin friction resistance τ_{mf} can be defined on the pile shaft or calculated according to DIN 4014 or EA piles.

1.6.3 Project Identification

In the program, it must be distinguished between the following two data groups:

1 System data (For identification of the project that is created and information to the output for the printer).

2 Soil data (Soil properties and so on).

The defining input data for these data groups is carried out as follows:

After clicking on the "Project Identification" option, the following general project data are defined (Figure 6):

Title: Title label
Date: Date
Project: Project label

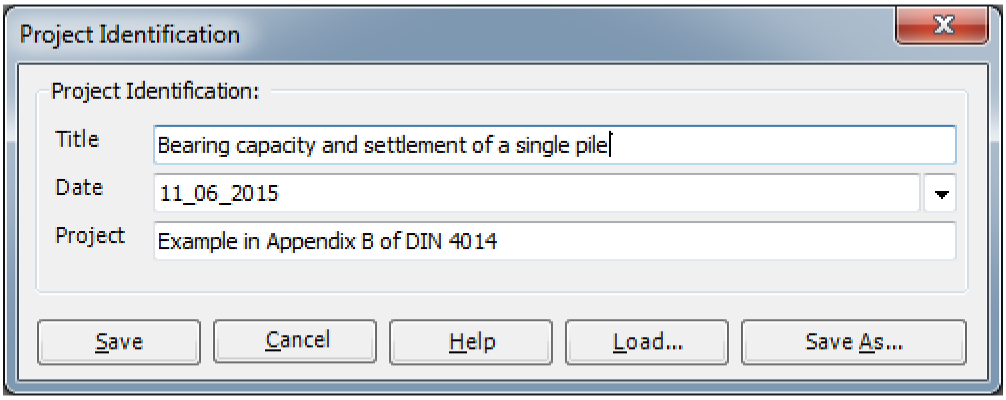


Figure 6 Project Identification

1.6.4 System data of the pile

After clicking on the "Bearing capacity and settlement of single pile or pile wall" option, the following system data of the pile are defined (Figure 7):

Calculation task:

- Analysis of single pile
- Analysis of pile wall

und load settlement curve of pile according to

- DIN 4014
- EA-Piles for lower table values
- EA-Piles for upper table values

System data of piles

D	Pile diameter [m]
Pz	Pile label

For a single pile

Ipf	Pile No.
Df	Pile toe diameter [m]
Qv	Load on pile head [MN]

while for a pile wall

Ipf	Pile wall No.
Wl	Wall width [m]
Abst	Pile distance [m]
Npf	Number of piles

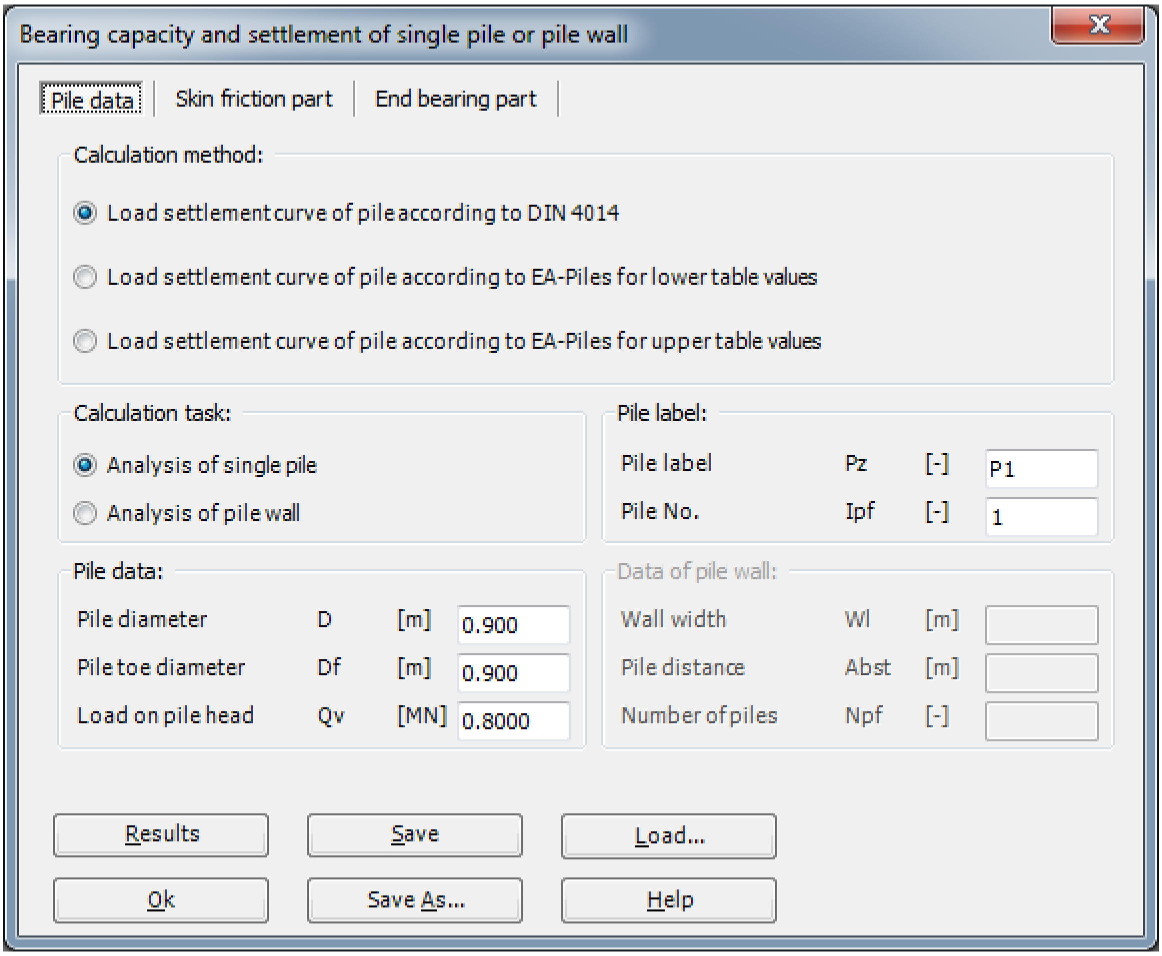


Figure 7 Pile data

1.6.5 Data of skin friction on the pile shaft

The soil conditions or the ultimate skin friction on the pile shaft are determined according to Table 4 (for non cohesion soil) or Table 5 (for cohesion soil). The first defining is (Figure 8):

ANSCH Number of soil layers in the pile shaft zone (above the pile tip).

Then, the data for skin friction on the pile shaft for each of the ANSCH layers *i* are defined. There are also three possibilities for this:

1. Direct input of the ultimate skin friction value *Tau* (*i*)

2. Defining mean CPT cone resistance q_s (*i*)
and automatic evaluation of the DIN-Table 4
(for non-cohesive soil with cone resistance q_s, see section 1.3)

3. Defining the shear strength c_u (*i*) of the undrained soil and automatic evaluation of the DIN- Table 5 (for cohesion soil with the shear strength c_u, see section 1.3).

In the form of Figure 8, if the option "The values of the table 4 or 5 from DIN 4014 are taken into account" is checked, the program will calculate the value of *Tau* (*i*) from Tables 4 or 5 of the standard DIN 4014 by linear interpolation from the cone resistance q_s (*i*) (Table 4) or from shear strength c_u (*i*) (Table 5). If the previous option is unchecked, the ultimate skin friction *Tau* (*i*) [MN/m^2] for each layer *i* is defined.

The following values are then defined in the form of Figure 8 for the ANSCH layers:

$L1(i)$ Thickness of the layer *i* [m].

In the case of check the previous option, the soil parameters q_s (*i*) or c_u (*i*) are defined for each layer, and the ultimate skin friction *Tau* (*i*) are determined by interpolation from one of the two following soil parameters.

q_s (*i*) Penetration resistance [MN/m^2]
for non-cohesive soil.
Determining the ultimate skin friction *Tau* (*i*) from Table 4 of the standard DIN 4014 by linear interpolation.

or, undrainage cohesion of the layer is defined:

c_u (*i*) Undrainage cohesion [MN/m^2] of the layer *i*
for cohesive soil.
Determining the ultimate skin friction *Tau* (*i*) from Table 5 of the standard DIN 4014 by linear interpolation.

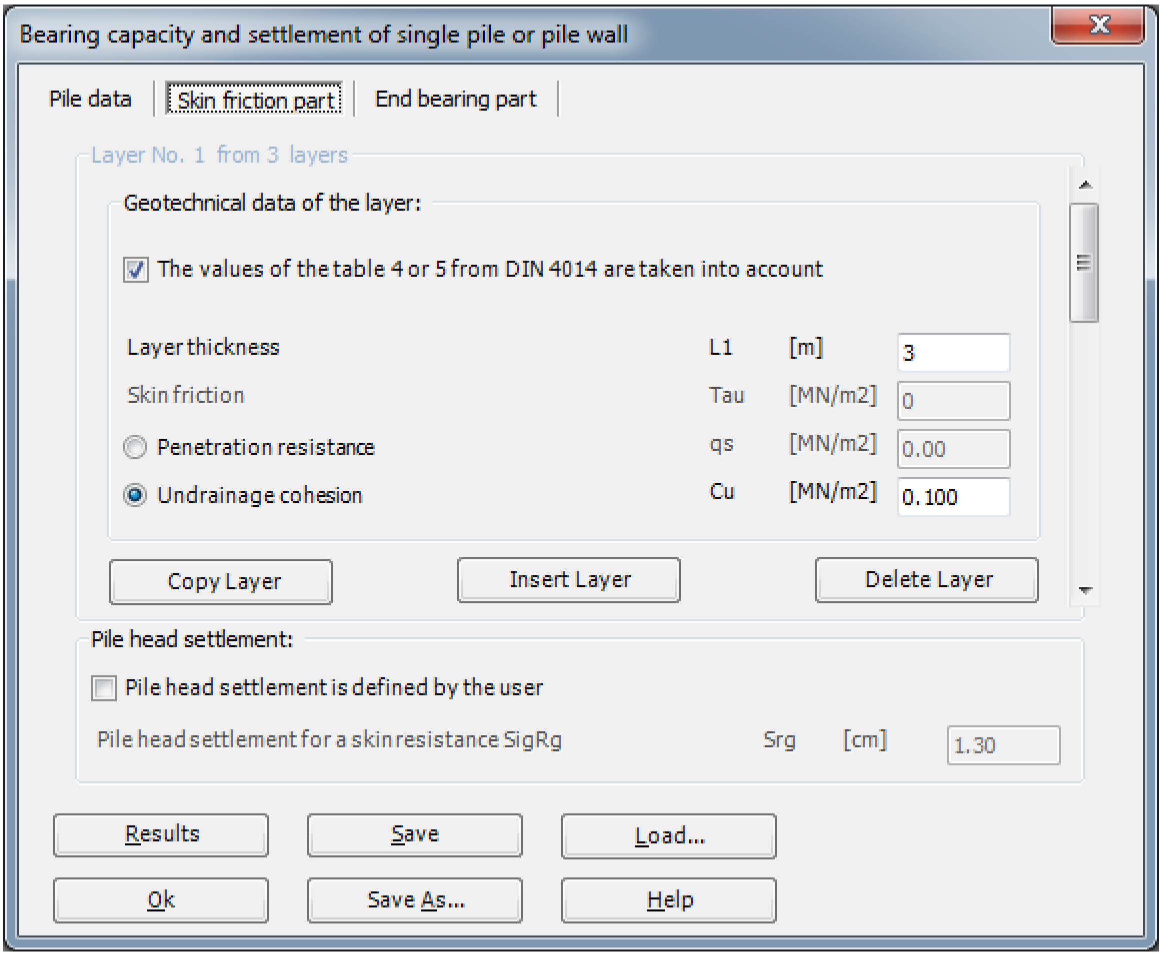


Figure 8 Soil profile

1.6.6 Soil data under the pile tip

Then, the soil data under the pile tip are defined (Figure 9):

q_s Penetration resistance under the pile tip q_s [MN/m^2] in a zone of 3 *D* for non-cohesive soil

or

c_u Undrainage cohesion c_u [MN/m^2] under the pile tip for cohesive soil.

In the form of Figure 9, if the option "The values of the table 1 or 2 from DIN 4014 are taken into account" is checked, the program will calculate the value of *Sigma-s* (*Sig*) from Table 1 or 2 of the standard DIN 4014 by linear interpolation from Table 1 for non-cohesive soil or from Table 2 for cohesive soil. If the previous option is unchecked, the three values of *Sig* related to the ratio *s/D* are defined as follows:

Sig	Pile tip resistance [MN/m^2] for the pile head settlement related to the pile diameter *s/D* = 0.02
*Sig*1	Pile tip resistance [MN/m^2] for the pile head settlement related to the pile diameter *s/D* = 0.03
SigGr	Pile tip resistance [MN/m^2] for the pile head settlement related to the pile diameter *s/D* = 0.10.

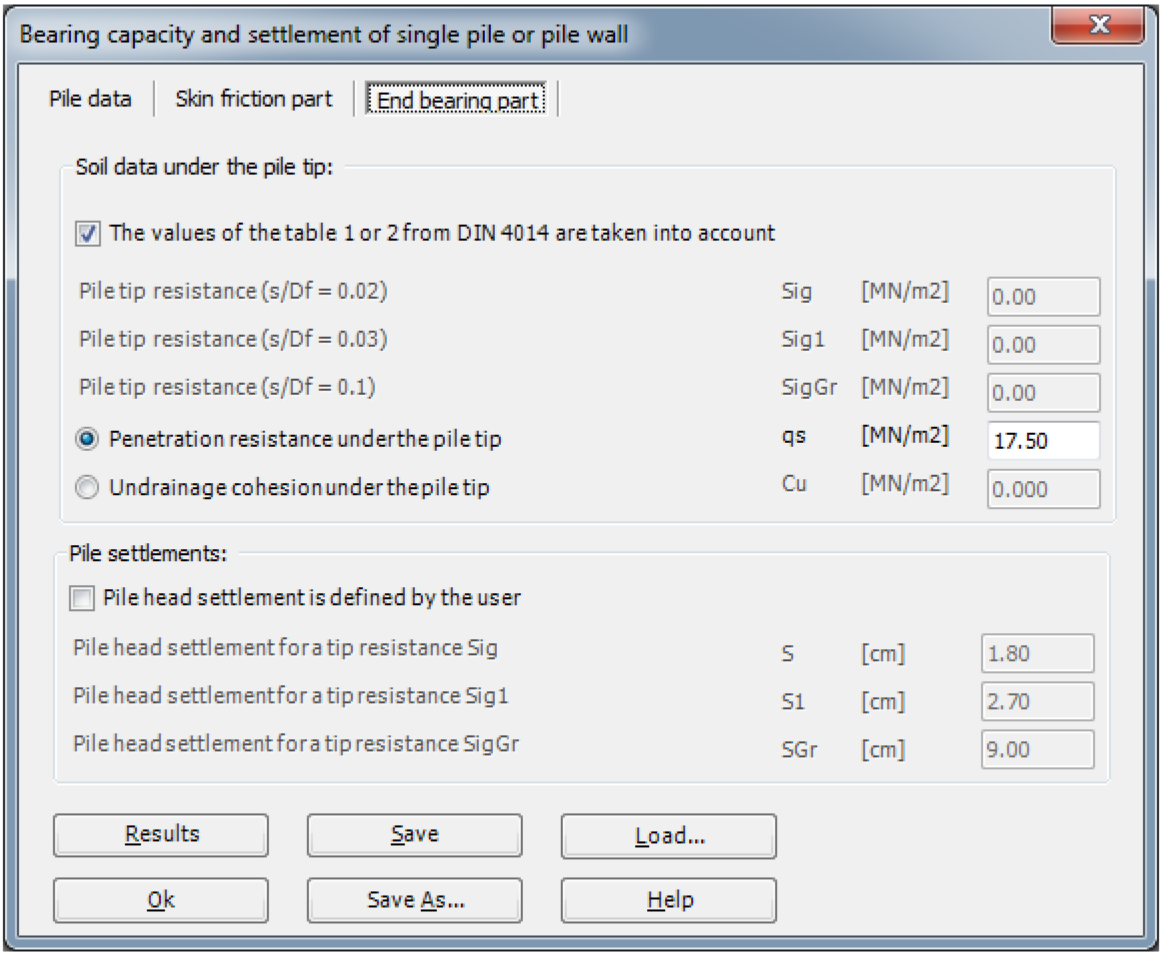


Figure 9 Soil data under the pile tip

1.7 Numerical Examples

1.7.1 Introduction

The application possibilities of the program *GEO Tools* are presented below in some numerical examples.

1.7.2 Example 1: Bearing capacity of a single pile (DIN 4014)

1.7.2.1 Description of the problem

The bearing capacity of a single pile is required to be determined by the program *GEO Tools* according to DIN 4014. The same pile example, which can also be found in the Appendix B of DIN 4014 is chosen. Figure 10 and Table 11 summarized the information relating to the soil type, soil strength and pile geometry required for determining the ultimate load capacity of the pile Q (s). It is also required to determine the safety factor for a bored pile having a design load of Q_v = 1.5 [MN].

Table 11 Soil properties

Layer No.	Soil	Layer thickness $L_1(i)$ [m]	Penetrometer tip resistance $q_s(i)$ [MN/m]	Undrained shear strength $c_u(i)$ [MN/m^2]
1	Fill	2.2	0.05	- - -
2	Clay	3.0	- - -	0.10
3	Sand	2,5	7.00	- - -
4	Sand	2,5	11.00	- - -
5 (under the pile base)	Sand	$3 \times D_f = 2.7$	17.50	- - -

1.7.2.2 Solving the problem

As shown in Figure 10, the thin fill stratum of thickness $L_1(1)$ = 2.2 [m] is hardly resistant to the penetrometer. Therefore its resistance can be neglected.

In the clay stratum of thickness $L_1(2)$ = 3 [m] in the depth from 2.2 [m] to 5.2 [m], the tip resistance is defined by the undrained shear strength of the soil, where $c_u(2)$ = 0.1 [MN/m^2]. The ultimate skin friction for this layer, τ_{mf}, of undarined shear strength $c_u(2)$ = 0.1 [MN/m^2] may be taken as τ_{mf} = 0.04 [MN/m] according to Table 5.

The penetrometer tip resistance in sand stratum until a depth about 15 [m] is expressed in the form of conservative averages, q_{s2}, q_{s3} and q_s, which relate to depth ranges, as illustrated in Figure 10.

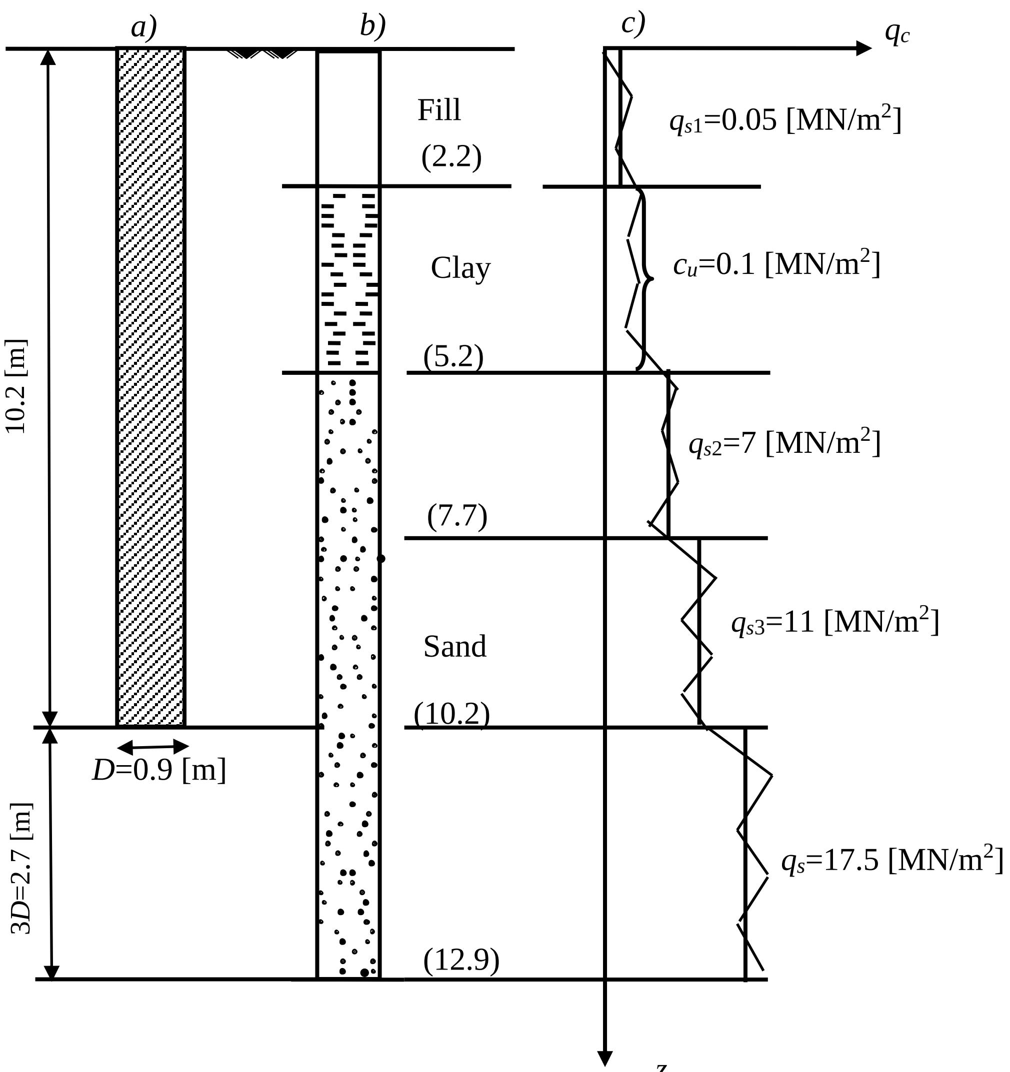


Figure 10 Soil profile, sounding graph and pile dimensions for determination of load-settlement curve

1.7.2.3 Hand calculation

The hand calculation is carried out according to the following steps:

1.7.2.3.1 Calculation of the characteristic pile tip resistance Qs(s):

The pile base area is:

$$A_f = \frac{\pi D_f^2}{4} = \frac{\pi (0.9)^2}{4} = 0.636\,[\mathrm{m}^2]$$

For the determination of the pile tip resistance σ(*s*), the strength of the ground to the depth ≥ 3*D* or 1,5 [m], in the example to 3 × 0.9 = 2.7 [m] below the pile base is decided.

For penetrometer tip resistance q_s = 17,5 [MN/m^2], the tip resistance of the pile σ [MN/m^2] is obtained according to Table 1 of DIN 4014 for the related pile head settlement to pile diameter s/D_f. Where q_s is an average penetrometer tip resistance, intermediate values may be linearly interpolated.

Tip resistance of the pile σ [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.02

$$\sigma = 1.05 + (1.4 - 1.05)\frac{20-17.5}{20-15}$$
$$\sigma = 1.225\,[\mathrm{MN/m^2}]$$

Tip resistance of the pile σ_1 [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.03

$$\sigma_1 = 1.35 + (1.8 - 1.35)\frac{20-17.5}{20-15}$$
$$\sigma_1 = 1.575\,[\mathrm{MN/m^2}]$$

Tip resistance of the pile σ_{gr} [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.10

$$\sigma_{gr} = 3.0 + (3.5 - 3.0)\frac{20-178.5}{20-15}$$
$$\sigma_{gr} = 3.25\,[\mathrm{MN/m^2}]$$

Pile tip resistances $Qs(s)$ are:

$$Q_s(s)_1 = \sigma \times A_f = 1.225 \times 0.636 = 0.779\,[\mathrm{MN}]$$
$$Q_s(s)_2 = \sigma_1 \times A_f = 1.575 \times 0.636 = 1.002\,[\mathrm{MN}]$$
$$Q_s(s)_3 = \sigma_{gr} \times A_f = 3.25 \times 0.636 = 2.067\,[\mathrm{MN}]$$

The corresponding pile head settlements s are:

$$s_1 = 0.02 D_f = 0.02 \times 0.9 = 0.0018\,[\mathrm{m}] = 1.8\,[\mathrm{cm}]$$
$$s_2 = 0.03 D_f = 0.03 \times 0.9 = 0.0027\,[\mathrm{m}] = 2.7\,[\mathrm{cm}]$$
$$s_3 = 0.10 D_f = 0.10 \times 0.9 = 0.090\,[\mathrm{m}] = 9.0\,[\mathrm{cm}]$$

1.7.2.3.2 Calculation of the characteristic pile skin friction resistance Q_{rg}:

The pile surface area is:

$$A_m = \pi D_f \times 1.0 = 0.9\pi \times 1.0 = 2.827 \text{ [m}^2\text{/m]}$$

Fill: It does not provide a significant proportion and it is neglected.

Clay layer: Layer thickness L_1 = 3.0 [m], for c_{u1} = 0.1 [MN/m^2] the pile skin friction τ_{mf1} according to Table 5 of DIN 4014 is:

$$\tau_{mf1} = 0.04 \text{ [MN/m}^2\text{]}$$

Therefore:

$$Q_{rg_1} = \tau_{mf1} \times A_m \times L_1 = 0.04 \times 2.827 \times 3.0 = 0.339 \text{ [MN]}$$

Sand layer: Layer thickness L_2 = 2.5 [m], for q_{s2} = 7 [MN/m^2] the pile skin friction τ_{mf2} according to Table 4 of DIN 4014 is:

$$\tau_{mf2} = 0.04 + (0.08 - 0.04)\frac{7-5}{10-5}$$

$$\tau_{mf2} = 0.056 \text{ [MN/m}^2\text{]}$$

Therefore:

$$Q_{rg_2} = \tau_{mf2} \times A_m \times L_2 = 0.056 \times 2.827 \times 2.5 = 0.396 \text{ [MN]}$$

Sand layer above the pile base: Layer thickness L_3 = 2.5 [m], for q_{s3} = 11 [MN/m^2] the pile skin friction τ_{mf3} according to Table 4 of DIN 4014 is:

$$\tau_{mf3} = 0.08 + (0.12 - 0.08)\frac{11-10}{15-10}$$

$$\tau_{mf3} = 0.088 \text{ [MN/m}^2\text{]}$$

Therefore:

$$Q_{rg_3} = \tau_{mf3} \times A_m \times L_3 = 0.088 \times 2.827 \times 2.5 = 0.622 \text{ [MN]}$$

Total skin friction force:

$$Q_{rg} = Q_{rg_1} + Q_{rg_2} + Q_{rg_3} = 0.339 + 0.396 + 0.622 = 1.357 \text{ [MN]}$$

Calculation of the characteristic pile skin friction resistance Q_{rg} is presented in the Table 12.

Table 12 Ultimate skin resistance in stratum *i* as a function of pile shaft area, penetrometer tip resistance and ultimate skin friction resistance

Layer thickness $L1$ [m]	Penetrometer tip resistance q_s [MN/m²]	Undrained shear strength of the soil c_u [MN/m²]	Skin friction τ_{mf} [MN/m²]	Skin friction force Q_{rg} [MN]
3,0	-	0,1	0,040	0,339
2,5	7	-	0,056	0,396
2,5	11	-	0,088	0,622
Total skin friction force Q_{rg}				1,357

The pile head settlement s_{rg} is obtained from:

$$s_{rg} = 0.5Q_{rg}\,(\text{in [MN]}) + 0.5 < 3\,[\text{cm}]$$
$$s_{rg} = 0.5 \times 1.357 + 0.5 = 1.2\,[\text{cm}]$$

The pile tip resistance $Q_s(s)$ for s_{rg} = 1.2 [cm] is:

$$Q_s(s) = \frac{s_{rg}}{s_1} \times Q_s(s)_1$$
$$Q_s(s) = \frac{1.2}{1.8} \times 0.779 = 0.519\,[\text{MN}]$$

Pile resistance $Q(s)$ as a function of pile head settlement is presented in Table 13.

Table 13 Pile resistance $Q(s)$ as a function of pile head settlement

Relative pile head settlement $\frac{S}{D_f}$ [-]	Pile head settlement s [cm]	Pile tip resistance $Q_s(s)$ [MN]	Pile skin resistance $Q_r(s)$ [MN]	Pile resistance $Q(s)$ [MN]
0.013	1,20	0,519	1,357	1,876
0.02	1,80	0,779	1,357	2,136
0.03	2,70	1,002	1,357	2,359
0.10 = S_g	9,00	2,067	1,357	3,424= Q_g

1.7.2.3.3 Allowable pile load Q_{zul}:

From Table 13 the maximum pile resistance is Q_g = 3.424 [MN]. Then, allowable pile load Q_{zul} for a factor of safety η = 2.0 is:

$$Q_{zul} = \frac{Q_g}{\eta}$$

$$Q_{zul} = \frac{3.424}{2.0} = 1.712\,[\text{MN}]$$

1.7.2.3.4 Allowable pile settlement s_{zul}:

Allowable pile settlement s_{zul} for allowable pile load Q_{zul} = 1,712 [MN] is:

$$s_{zul} = s(1)\frac{Q_{zul}}{Q(1)}$$

$$s_{zul} = 1.2\frac{1.712}{1.876}$$

$$s_{zul} = 1.095\,[\text{cm}]$$

For Q_v = 1.5 [MN] the factor of safety η is:

$$\eta = \frac{Q_{zul}}{Q_v} = \frac{1.712}{1.5}$$

$$\eta = 1.14$$

1.7.2.3.5 Computer calculation

The input data and results of *GEO Tools* are presented on the next pages. Two pages of input data, intermediate and final results as well as a page of color diagram. By comparison, one can see a good agreement with hand calculation.

```
************************************************************
                        GEO Tools
                         Version 10
     Program authors Prof. M. El Gendy/ Dr. A. El Gendy
************************************************************
Title: Bearing capacity and settlement of a single pile
Date: 11_06_2015
Project: Example in Appendix B of DIN 4014
File: DIN 4014

------------------------------------------------------------
Bearing capacity and settlement of a single pile
Load settlement curve of pile according to DIN 4014
------------------------------------------------------------

Data:
Pile diameter                              D     [m]     = 0.90
Pile toe diameter                          Df    [m]     = 0.90
Pile length                                Lg    [m]     = 8.00
Pile label                                 Pz    [-]     = P1
Pile No.                                   Ipf=  [-]     = 1


Summary of results
Soil data under the pile tip:
Penetration resistance under the pile tip  qs    [MN/m2] = 17.50

Pile tip resistance (according to DIN 4014 Table 1)
s/Df = 0.02                                Sig   [MN/m2] = 1.23
s/Df = 0.03                                Sig1  [MN/m2] = 1.58
s/Df = 0.10                                SigGR [MN/m2] = 3.25


Internal results
Skin friction:
-------------------------------------------------------------
Layer      Layer  Penetration  Undrainage      Skin  Friction
  No.  thickness   resistance    cohesion  friction     force
                                  of soil
    I         L1           qs          Cu       Tau       Qrg
  [-]        [m]      [MN/m2]     [MN/m2]   [MN/m2]      [MN]
-------------------------------------------------------------
    1       3.00         ----       0.100      0.04     0.339
    2       2.50         7.00       -----      0.06     0.396
    3       2.50        11.00       -----      0.09     0.622
-------------------------------------------------------------
Sum of friction forces            Qrf          [MN] = 1.357

Load on pile head                 Qma+Qsp = Qv [MN] = 0.800
Skin friction part from Qv        Qma          [MN] = 0.581
End bearing part from Qv          Qsp          [MN] = 0.219
Expected settlement               sv           [cm] = 0.50
```

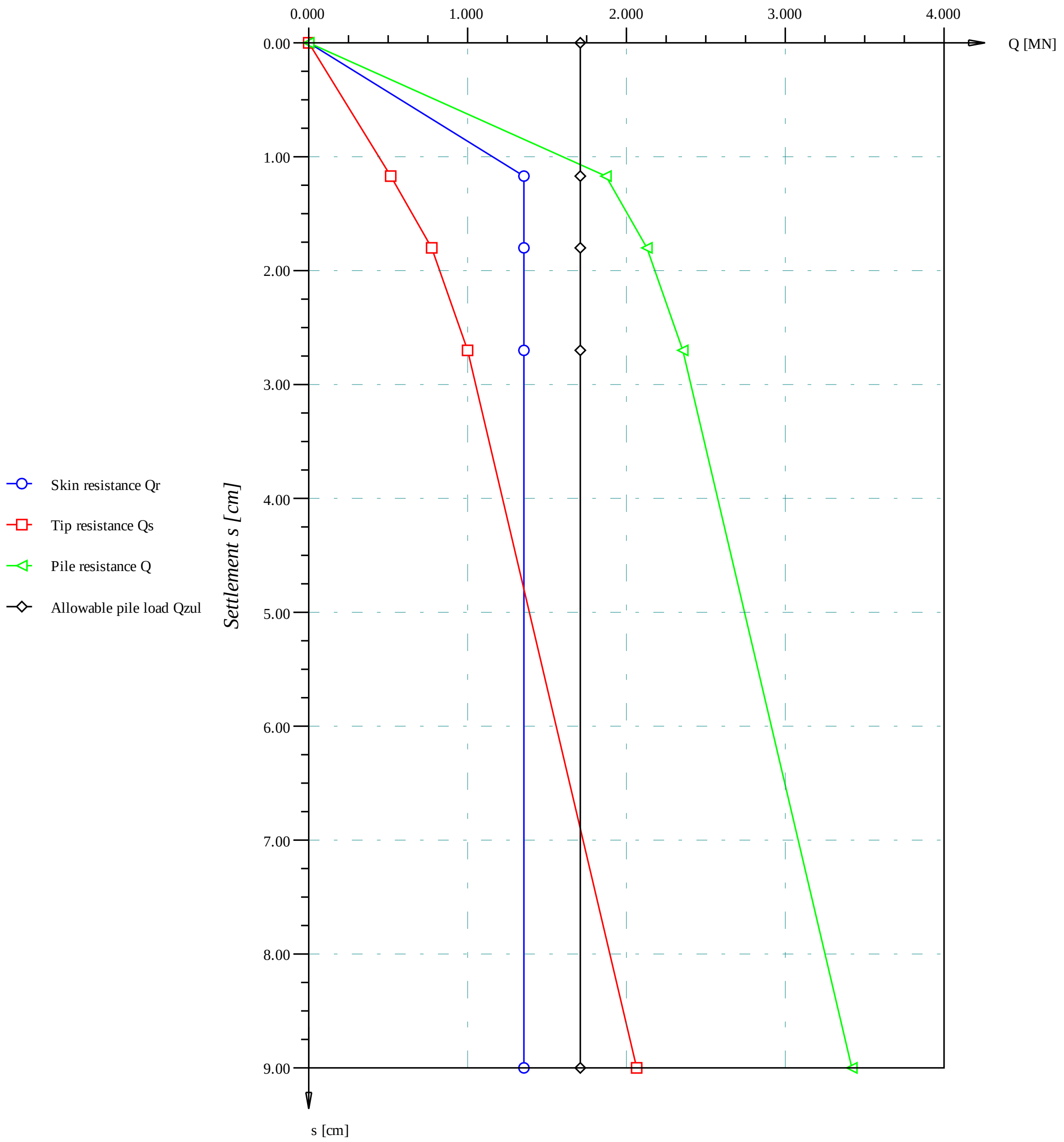
Pile resistance depending on pile settlement:

No. I [-]	Referred settlement s/Df [-]	Pile head settlement s [cm]	Pile friction resistance Qr [MN]	Tip resistance Qs [MN]	Pile resistance Q [MN]
1	0.01	1.18	1.357	0.510	1.867
2	0.02	1.80	1.357	0.779	2.136
3	0.03	2.70	1.357	1.002	2.359
4	0.10	9.00	1.357	2.068	3.425 = Qg=2*Qzul

```
Final results:
Allowable settlement        Szul              [cm] = 1.08
Allowable pile load         Qr+Qs = Qzul      [MN] = 1.712
Skin friction part          Qr                [MN] = 1.244
End bearing part            Qs                [MN] = 0.468
Safety factor               Qzul/QV = ETHA [-]  = 2.14
```

Pile label: P1

Pile No.: 1



Load settlement curve of pile according to DIN 4014

Ingenieurgemeinschaft G. Huber / R. Schulze Bachstrasse 12 in D-899 Neutal * Tel. 09262.9999	
Scale: 32	**Project: Example in Appendix B of DIN 4014**
File: DIN 4014	**Date: 11_06_2015**
Page No.:	**Title: Bearing capacity and settlement of a single pile**

1.7.3 Example 2: Bearing capacity of a single pile (*Simmer* 1999)

1.7.3.1 Description of the problem

The bearing capacity of a single pile is required to be determined by the program *GEO Tools* according to DIN 4014. The same pile example, which can also be found in the book of *Simmer* 1999 is chosen. Figure 11 and Table 14 summarized the information relating to the soil type, soil strength and pile geometry required for determining the ultimate load capacity of the pile Q (s). It is also required to determine the design load Q_v for allowable pile settlement of s= 2 [cm] and then the safety factor for the design load Q_v.

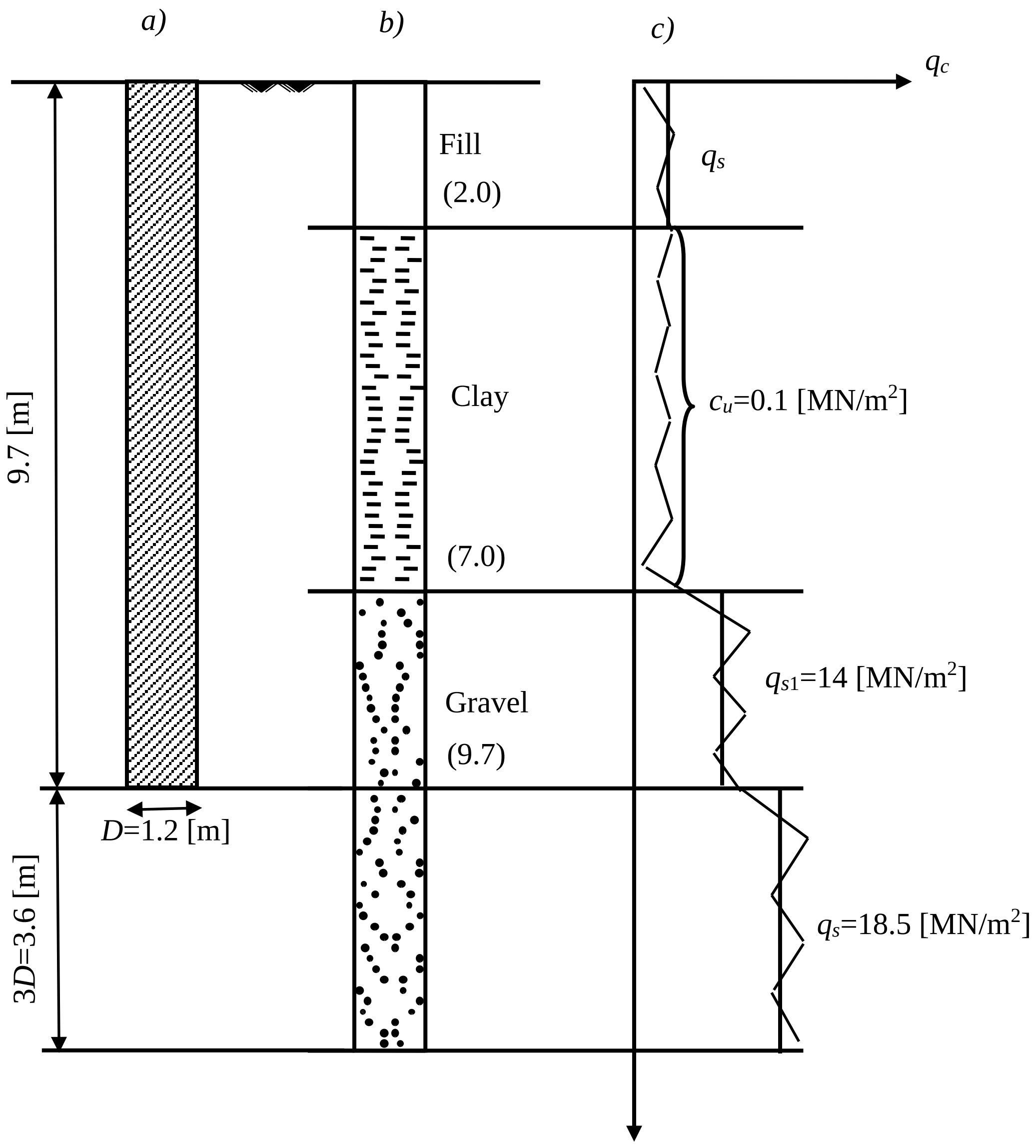


Figure 11 Soil profile, sounding graph and pile dimensions for determination of load-settlement curve

1.7.3.2 Solving the problem

As shown in Figure 11, the thin fill stratum of thickness $L_1(1) = 2.0$ [m] is hardly resistant to the penetrometer. Therefore its resistance can be neglected.

In the clay stratum of thickness $L_1(2) = 5$ [m] in the depth from 2.0 [m] to 7.0 [m], the tip resistance is defined by the undrained shear strength of the soil, where $c_u(2) = 0.1$ [MN/m^2]. The ultimate skin friction for this layer, τ_{mf}, of undarined shear strength $c_u(2) = 0.1$ [MN/m^2] may be taken as $\tau_{mf} = 0.04$ [MN/m] according to Table 5.

The penetrometer tip resistance in gravel stratum until a depth about 13.3 [m] is expressed in the form of conservative averages, q_{s1} and q_s, which relate to depth ranges, as illustrated in Figure 4.

Table 14 Soil properties

Layer No.	Soil	Layer thickness $L_1(i)$ [m]	Penetrometer tip resistance $q_s(i)$ [MN/m^2]	Undrained shear strength c_u(i) [MN/m^2]
1	Fill	2.0	0.05	- - -
2	Clay	5.0	- - -	0.10
3	Gravel	9.7	14,0	- - -
4 (under the pile base)	Gravel	$3 \times D_f = 3.6$	18.5	- - -

1.7.3.3 Hand calculation

The hand calculation is carried out according to the following steps:

1.7.3.3.1 Calculation of the characteristic pile tip resistance Qs(s):

The pile base area is:

$$A_f = \frac{\pi D_f^2}{4} = \frac{\pi (1.2)^2}{4} = 1.13 [\text{m}^2]$$

For the determination of the pile tip resistance σ(*s*), the strength of the ground to the depth ≥ 3*D* or 1,5 [m], in the example to 3×1,2 = 3,6 [m] below the pile base is decided.

For penetrometer tip resistance q_s = 18,5 [MN/m^2], the tip resistance of the pile σ [MN/m^2] is obtained according to Table 1 of DIN 4014 for the related pile head settlement to pile diameter s/D_f. Where q_s is an average penetrometer tip resistance, intermediate values may be linearly interpolated.

Tip resistance of the pile σ [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.02

$$\sigma = 1.05 + (1.4 - 1.05)\frac{20-18.5}{20-15}$$
$$\sigma = 1.30\,[\mathrm{MN/m^2}]$$

Tip resistance of the pile σ_1 [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.03

$$\sigma_1 = 1.35 + (1.8 - 1.35)\frac{20-18.5}{20-15}$$
$$\sigma_1 = 1.67\,[\mathrm{MN/m^2}]$$

Tip resistance of the pile σ_{gr} [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.10

$$\sigma_{gr} = 3.0 + (3.5 - 3.0)\frac{20-18.5}{20-15}$$
$$\sigma_{gr} = 3.35\,[\mathrm{MN/m^2}]$$

Pile tip resistances $Qs(s)$ are:

$$Q_s(s)_1 = \sigma \times A_f = 1.30 \times 1.13 = 1.47\,[\mathrm{MN}]$$
$$Q_s(s)_2 = \sigma_1 \times A_f = 1.67 \times 1.13 = 1.89\,[\mathrm{MN}]$$
$$Q_s(s)_3 = \sigma_{gr} \times A_f = 3.35 \times 1.13 = 3.79\,[\mathrm{MN}]$$

The corresponding pile head settlements s are:

$$s_1 = 0.02 D_f = 0.02 \times 1.2 = 0.0024\,[\mathrm{m}] = 2.4\,[\mathrm{cm}]$$
$$s_2 = 0.03 D_f = 0.03 \times 1.2 = 0.0036\,[\mathrm{m}] = 3.6\,[\mathrm{cm}]$$
$$s_3 = 0.10 D_f = 0.10 \times 1.2 = 0.1200\,[\mathrm{m}] = 12.0\,[\mathrm{cm}]$$

1.7.3.3.2 Calculation of the characteristic pile skin friction resistance Q_{rg}:

The pile surface area is:

$$A_m = \pi D_f \times 1.0 = 1.2\pi \times 1.0 = 3.77\,[\mathrm{m^2/m}]$$

Fill: It does not provide a significant proportion and it is neglected.

Clay layer: Layer thickness L_1 = 5.0 [m], for c_{u1} = 0.1 [MN/m^2] the pile skin friction τ_{mf1} according to Table 5 of DIN 4014 is:

$$\tau_{mf1} = 0.04 \text{ [MN/m}^2\text{]}$$

Therefore:

$$Q_{rg\,1} = \tau_{mf\,1} \times A_m \times L_1 = 0.04 \times 3.77 \times 5.0 = 0.75 \text{ [MN]}$$

Gravel layer: Layer thickness L_2 = 9.70 [m], for q_{s2} = 14 [MN/m^2] the pile skin friction τ_{mf2} according to Table 4 of DIN 4014 is:

$$\tau_{mf\,2} = 0.08 + (0.12 - 0.08)\frac{15-14}{15-10}$$

$$\tau_{mf\,2} = 0.112 \text{ [MN/m}^2\text{]}$$

Therefore:

$$Q_{rg\,2} = \tau_{mf\,2} \times A_m \times L_2 = 0.112 \times 3.77 \times 2.7 = 1.12 \text{ [MN]}$$

Total skin friction force:

$$Q_{rg} = Q_{rg\,1} + Q_{rg\,2} = 0.75 + 1.12 = 1.87 \text{ [MN]}$$

Calculation of the characteristic pile skin friction resistance Q_{rg} is presented in the Table 15.

Table 15 Ultimate skin resistance in stratum *i* as a function of pile shaft area, penetrometer tip resistance and ultimate skin friction resistance

Layer thickness *L*1 [m]	Penetrometer tip resistance q_s [MN/m^2]	Undrained shear strength of the soil c_u [MN/m^2]	Skin friction τ_{mf} [MN/m^2]	Skin friction force Q_{rg} [MN]
5	-	0,1	0,040	0,75
7	14	-	0,112	1,12
Total skin friction force Q_{rg}				1,87

The pile head settlement s_{rg} is obtained from:

$$s_{rg} = 0.5 Q_{rg} \text{ (in [MN])} + 0.5 < 3 \text{ [cm]}$$

$$s_{rg} = 0.5 \times 1.87 + 0.5 = 1.4 \text{ [cm]}$$

The pile tip resistance $Q_s(s)$ for s_{rg} = 1.4 [cm] is:

$$Q_s(s) = \frac{s_{rg}}{s_1} \times Q_s(s)_1$$

$$Q_s(s) = \frac{1.4}{2.4} \times 1.47 = 0.86\,[\mathrm{MN}]$$

Pile resistance $Q(s)$ as a function of pile head settlement is presented in Table 16.

Table 16 Pile resistance $Q(s)$ as a function of pile head settlement

Relative pile head settlement $\frac{S}{D_f}$ [-]	Pile head settlement s [cm]	Pile tip resistance $Q_s(s)$ [MN]	Pile skin resistance $Q_r(s)$ [MN]	Pile resistance $Q(s)$ [MN]
0.012	1.40	0.86	1.87	2.73
0.02	2.40	1.47	1.87	3.34
0.03	3.60	1.89	1.87	3.76
0.10 = S_g	12.00	3.79	1.87	5.66 = Q_g

1.7.3.3.3 Allowable pile load Q_{zul}:

From Table 16 the maximum pile resistance is Q_g = 5.66 [MN]. Then, allowable pile load Q_{zul} for a factor of safety η = 2.0 is:

$$Q_{zul} = \frac{Q_g}{\eta}$$

$$Q_{zul} = \frac{5.66}{2.0} = 2.83\,[\mathrm{MN}]$$

1.7.3.3.4 Allowable pile settlement s_{zul}:

Allowable pile settlement s_{zul} for allowable pile load Q_{zul} = 2.83 [MN] is:

$$s_{zul} = s(1) + \left(Q_{zul} - Q(1)\right)\frac{s(2) - s(1)}{Q(2) - Q(1)}$$

$$s_{zul} = 1.4 + (2.83 - 2.73)\frac{2.4 - 1.4}{3.34 - 2.73}$$

$$s_{zul} = 1.56\,[\mathrm{cm}]$$

For allowable settlement s = 2.0 [cm] the pile load Q_v is:

$$Q_v = Q(1) + \left(Q(2) - Q(1)\right)\frac{s - s(1)}{Q(2) - Q(1)}$$

$$Q_v = 2.73 + \left(3.34 - 2.73\right)\frac{2.0 - 1.4}{2.4 - 1.4}$$

$$Q_v = 3.10\,[\text{MN}] > Q_{zul}$$

For Q_v = 3,1 [MN] the factor of safety η is:

$$\eta = \frac{Q_{zul}}{Q_v} = \frac{2.83}{3.1}$$

$$\eta = 0.9$$

1.7.3.3.5 Computer calculation

The input data and results of *GEO Tools* are presented on the next pages. Two pages of input data, intermediate and final results as well as a page of color diagram. By comparison, one can see a good agreement with hand calculation of *Simmer* 1999.

```
************************************************************
                        GEO Tools
                         Version 10
     Program authors Prof. M. El Gendy/ Dr. A. El Gendy
************************************************************
Title: Bearing capacity and settlement of a single pile
Date: 11_06_2015
Project: Grundbau Teil 2, Simmer (1999) Example 23, Page 300
File: Simmer (1999)

------------------------------------------------------------
Bearing capacity and settlement of a single pile
Load settlement curve of pile according to DIN 4014
------------------------------------------------------------

Data:
Pile diameter                              D     [m]     = 1.20
Pile toe diameter                          Df    [m]     = 1.20
Pile length                                Lg    [m]     = 7.70
Pile label                                 Pz    [-]     = P1
Pile No.                                   Ipf=  [-]     = 1


Summary of results
Soil data under the pile tip:
Penetration resistance under the pile tip  qs    [MN/m2] = 18.50

Pile tip resistance (according to DIN 4014 Table 1)
s/Df = 0.02                                Sig   [MN/m2] = 1.30
s/Df = 0.03                                Sig1  [MN/m2] = 1.67
s/Df = 0.10                                SigGR [MN/m2] = 3.35


Internal results
Skin friction:
-------------------------------------------------------------
Layer      Layer  Penetration  Undrainage      Skin  Friction
  No.  thickness   resistance    cohesion  friction     force
                                  of soil
    I         L1           qs          Cu       Tau       Qrg
  [-]        [m]      [MN/m2]     [MN/m2]   [MN/m2]      [MN]
-------------------------------------------------------------
    1       5.00         ----       0.100      0.04     0.754
    2       2.70        14.00       -----      0.11     1.140
-------------------------------------------------------------
Sum of friction forces            Qrf           [MN] = 1.894

Load on pile head                 Qma+Qsp = Qv  [MN] = 3.100
Skin friction part from Qv        Qma           [MN] = 1.894
End bearing part from Qv          Qsp           [MN] = 1.206
Expected settlement               sv            [cm] = 1.98
```

Pile resistance depending on pile settlement:

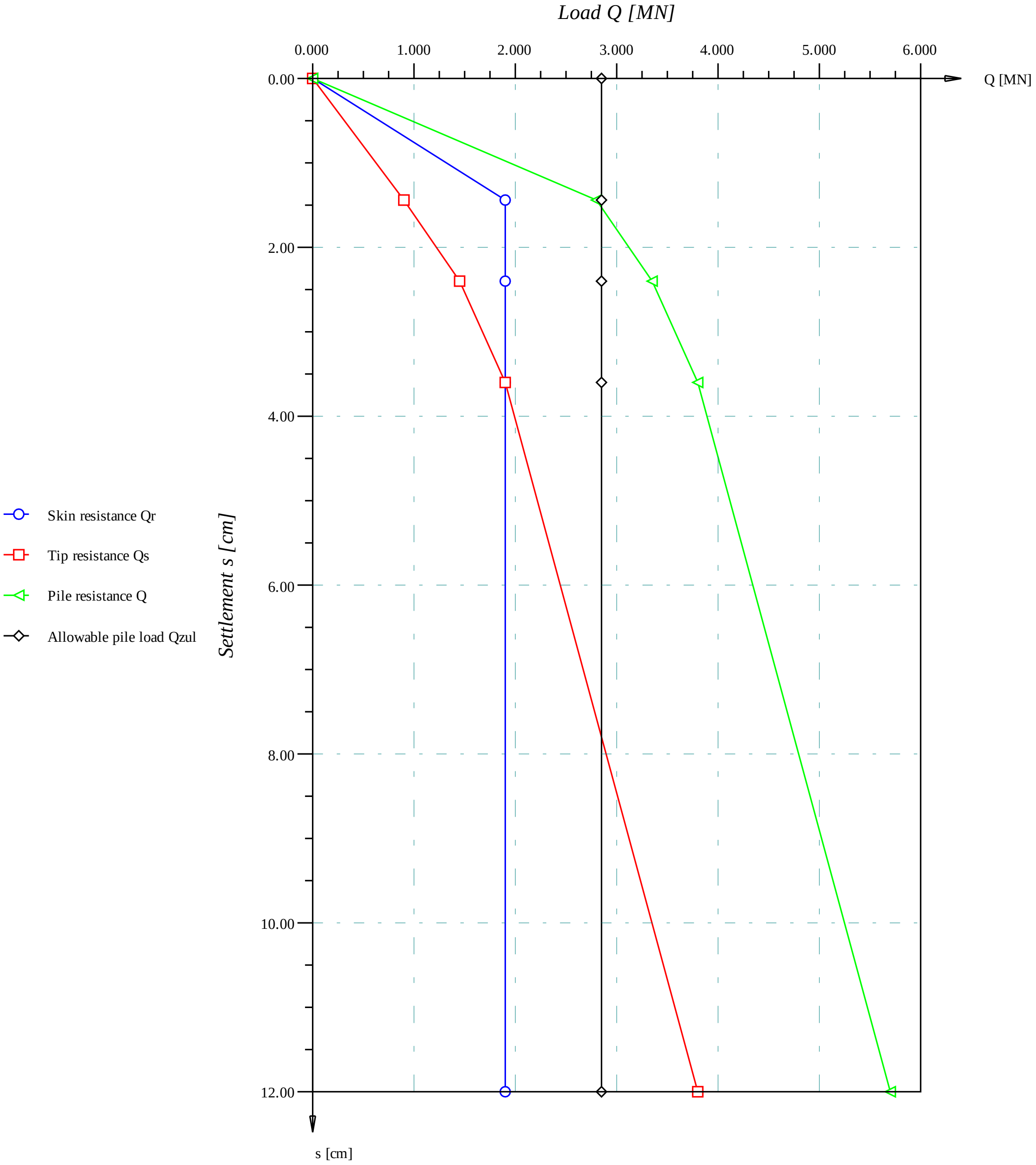
No. I [-]	Referred settlement s/Df [-]	Pile head settlement s [cm]	Pile friction resistance Qr [MN]	Tip resistance Qs [MN]	Pile resistance Q [MN]
1	0.01	1.45	1.894	0.883	2.777
2	0.02	2.40	1.894	1.465	3.359
3	0.03	3.60	1.894	1.883	3.777
4	0.10	12.00	1.894	3.789	5.683 = Qg=2*Qzul

Final results:

Allowable settlement	Szul	[cm]	= 1.55
Allowable pile load	Qr+Qs = Qzul	[MN]	= 2.841
Skin friction part	Qr	[MN]	= 1.894
End bearing part	Qs	[MN]	= 0.947
Safety factor	Qzul/QV = ETHA	[-]	= 0.92

Pile label: P1

Pile No.: 1



Load settlement curve of pile according to DIN 4014

<table>
<tr><td colspan="2">Ingenieurgemeinschaft G. Huber / R. Schulze
Bachstrasse 12 in D-899 Neutal * Tel. 09262.9999</td></tr>
<tr><td>Scale: 50</td><td>Project: Grundbau Teil 2, Simmer (1999) Example 23, Page 300</td></tr>
<tr><td>File: Simmer (1999)</td><td>Date: 11_06_2015</td></tr>
<tr><td>Page No.:</td><td>Title: Bearing capacity and settlement of a single pile</td></tr>
</table>

1.7.4 Example 3: Bearing capacity of a pile wall

1.7.4.1 Description of the problem

It is required to determine the load settlement line for the pile wall shown in Figure 12. The pile wall consists of 9 piles with D = 0.9 [m] and extended to a depth of $L_1(1) = Lg$ = 15 [m]. The pile wall is W_l = 21 [m] wide in the horizontal direction. The pile load per pile is Q_v = 0.5 [MN].

The soil consists of sand extended to a depth of 18 [m]. A penetrometer tip resistance q_s = 8 [MN/m^2] was determined by CPT in the zone under the pile base. The pile shaft friction is set uniformly with *Tau* (1) = 0.02 [MN/m^2].

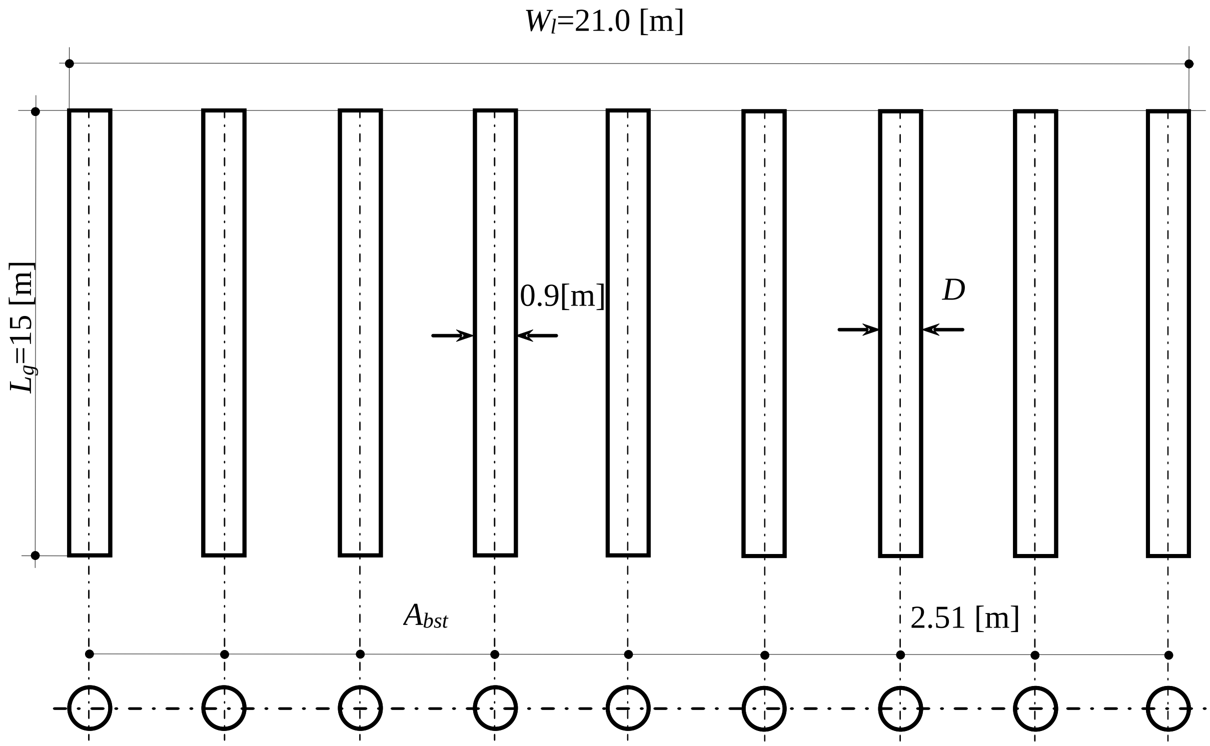


Figure 12 Dimension and data of the pile wall

1.7.4.2 Hand calculation

The hand calculation is carried out according to the following steps:

1.7.4.2.1 Calculation of the characteristic pile tip resistance Qs(s):

The pile base area is:

$$A_f = \frac{\pi D_f^2}{4} = \frac{\pi (0.9)^2}{4} = 0.636\,[\text{m}^2]$$

For the determination of the pile tip resistance σ(*s*), the strength of the ground to the depth ≥ 3*D* or 1,5 [m], in the example to 3 × 0.9 = 2.7 [m] below the pile base is decided.

For penetrometer tip resistance q_s = 8 [MN/m^2], the tip resistance of the pile σ [MN/m^2] is obtained according to Table 1 of DIN 4014 for the related pile head settlement to pile diameter s/D_f. Where q_s is an average penetrometer tip resistance, intermediate values may be linearly interpolated.

Tip resistance of the pile σ [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.02

$$\sigma = 0.7 \times \frac{8}{10}$$
$$\sigma = 0.56\,[\text{MN/m}^2]$$

Tip resistance of the pile σ_1 [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.03

$$\sigma_1 = 0.9 \times \frac{8}{10}$$
$$\sigma_1 = 0.72\,[\text{MN/m}^2]$$

Tip resistance of the pile σ_{gr} [MN/m^2] for the pile head settlement related to the pile diameter s/D_f = 0.10

$$\sigma_{gr} = 2.0 \times \frac{8}{10}$$
$$\sigma_{gr} = 1.6\,[\text{MN/m}^2]$$

1.7.4.2.2 Reduction factor ν

In the pile tip resistance for a pile wall, the values of Table 4 and Table 5 are to be reduced with the reduction factors ν according to Table 6 depending on the aspect side ratio.

Aspect side ratio:

$$\frac{W_l}{D_f} = \frac{21}{0.9} = 23.33[-] > 5$$

Reduction factor ν according to Table 6 of DIN 4014 is :

$$\nu = 0.6 \ [-]$$

Then the tip resistances after reduction are:

$$\sigma = 0.6 \times 0.56 = 0.336 [\text{MN/m}^2]$$
$$\sigma_1 = 0.6 \times 0.72 = 0.432 [\text{MN/m}^2]$$
$$\sigma_{gr} = 0.6 \times 1.6 = 0.96 [\text{MN/m}^2]$$

Pile tip resistances $Qs(s)$ are:

$$Q_s(s)_1 = \sigma \times A_f = 0.336 \times 0.636 = 0.214 [\text{MN}]$$
$$Q_s(s)_2 = \sigma_1 \times A_f = 0.432 \times 0.636 = 0.275 [\text{MN}]$$
$$Q_s(s)_3 = \sigma_{gr} \times A_f = 0.96 \times 0.636 = 0.611 [\text{MN}]$$

The corresponding pile head settlements *s* are:

$$s_1 = 0.02 D_f = 0.02 \times 0.9 = 0.018 [\text{m}] = 1.80 [\text{cm}]$$
$$s_2 = 0.03 D_f = 0.03 \times 0.9 = 0.027 [\text{m}] = 2.70 [\text{cm}]$$
$$s_3 = 0.10 D_f = 0.10 \times 0.9 = 0.090 [\text{m}] = 9.00 [\text{cm}]$$

1.7.4.2.3 Calculation of the characteristic pile skin friction resistance Q_{rg}:

The surface shaft area of the pile wall is:

$$u_w = (\pi D_f + (W_l - D_f) \times 2{,}0) \times 1{,}0$$
$$u_w = (0{,}9 \times \pi + (21 - 0{,}9) \times 2{,}0) \times 1{,}0 = 43.027 \ [\text{m}^2/\text{m}]$$

The shaft area for a single pile is:

$$A_m = \frac{u_w}{N_{pf}} = \frac{43.027}{9} = 4.781\left[\text{m}^2/\text{m}\right]$$

Pile skin resistance Q_{rg} is:

$$Q_{rg} = \tau_{mf} \times A_m \times L = 0.02 \times 4.781 \times 15 = 1.4343\,[\text{MN}]$$

Calculation of the characteristic pile friction resistance Q_{rg} is listed in Table 17.

Table 17 Ultimate skin resistance in stratum i as a function of pile shaft area, penetrometer tip resistance and ultimate skin friction resistance

Layer thickness $L1$ [m]	Penetrometer tip resistance q_s [MN/m^2]	Undrained shear strength of the soil c_u [MN/m^2]	Skin friction τ_{mf} [MN/m^2]	Skin friction force Q_{rg} [MN]
5	-	-	0,02	1,4343

The pile head settlement s_{rg} is obtained from:

$$s_{rg} = 0.5 Q_{rg}\,(\text{in [MN]}) + 0.5 < 3\,[\text{cm}]$$
$$s_{rg} = 0.5 \times 1.4343 + 0.5 = 1.217\,[\text{cm}]$$

The pile tip resistance $Q_s(s)$ for s_{rg} = 1.217 [cm] is:

$$Q_s(s) = \frac{s_{rg}}{s_1} \times Q_s(s)_1$$
$$Q_s(s) = \frac{1.217}{1.8} \times 0.214 = 0.145\left[\text{MN}\right]$$

Pile resistance $Q(s)$ as a function of pile head settlement is presented in Table 18.

Table 18 Pile resistance $Q(s)$ as a function of pile head settlement

Relative pile head settlement $\frac{S}{D_f}$ [-]	Pile head settlement s [cm]	Pile tip resistance $Q_s(s)$ [MN]	Pile skin resistance $Q_r(s)$ [MN]	Pile resistance $Q(s)$ [MN]
0.012	1.217	0.145	1.4343	1.5793
0.02	1.80	0.214	1.4343	1.6483
0.03	2.70	0.275	1.4343	1.7093
0.10 = S_g	9.0	0.611	1.4343	2.0453 = Q_g

1.7.4.2.4 Allowable pile load Q_{zul}:

From Table 18 the maximum pile resistance is Q_g = 2.0453 [MN]. Then, allowable pile load Q_{zul} for a factor of safety η = 2.0 is:

$$Q_{zul} = \frac{Q_g}{\eta}$$

$$Q_{zul} = \frac{2.0453}{2.0} = 1.023\,[\text{MN}]$$

1.7.4.2.5 Allowable pile settlement s_{zul}:

Allowable pile settlement s_{zul} for allowable pile load Q_{zul} = 1.023 [MN] is:

$$s_{zul} = s(1) - \frac{Q(1) - Q_{zul}}{Q(1)}\, s(1)$$

$$s_{zul} = 1.217 - \frac{1.579 - 1.023}{1.579} \times 1.217$$

$$s_{zul} = 0.788\,[\text{cm}]$$

For Q_v = 0.5 [MN] the factor of safety η is:

$$\eta = \frac{Q_{zul}}{Q_v} = \frac{1.023}{0.5}$$

$$\eta = 2.046$$

1.7.4.2.6 Computer calculation

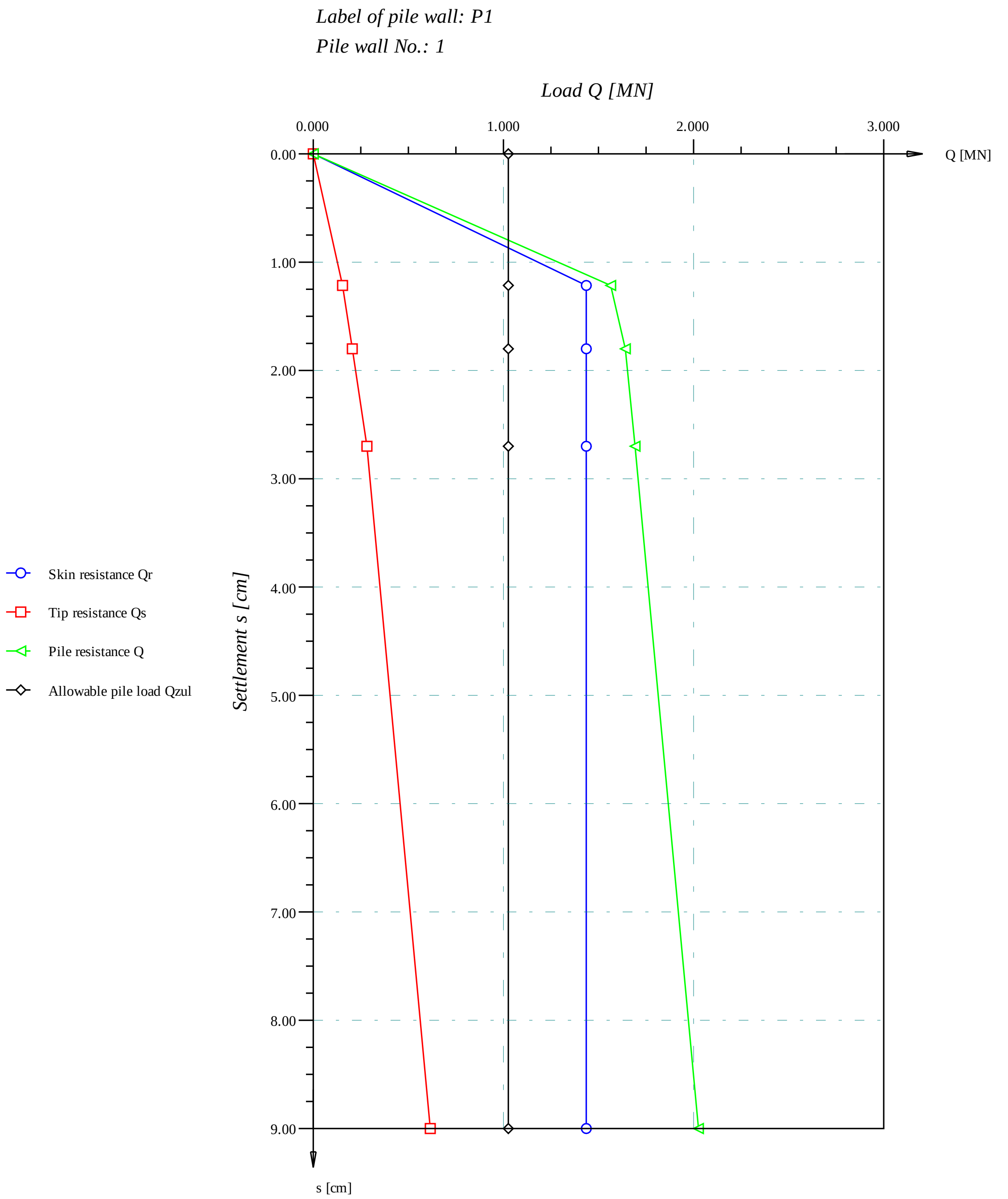
The input data and results of *GEO Tools* are presented on the next pages. Two pages of input data, intermediate and final results as well as a page of color diagram. By comparison, one can see a good agreement with hand calculation.

```
*************************************************************
                        GEO Tools
                         Version 10
     Program authors Prof. M. El Gendy/ Dr. A. El Gendy
*************************************************************
Title: Bearing capacity and settlement of a pile wall
Date: 11_06_2015
Project: Pile wall
File: Pile Wall

-------------------------------------------------------------
Bearing capacity and settlement of pile wall
Load settlement curve of pile according to DIN 4014
-------------------------------------------------------------

Data:
Pile diameter                             D       [m]     = 0.90
Pile toe diameter                         Df      [m]     = 0.90
Pile length                               Lg      [m]     = 15.00

Number of piles                           Npf     [-]     = 9
Wall width                                Wl      [m]     = 21.00
Pile distance                             Abst    [m]     = 2.51
Label of pile wall                        Pz      [-]     = P1
Pile wall No.                             Ipf     [-]     = 1


Summary of results
Soil data under the pile tip:
Penetration resistance under the pile tip qs      [MN/m2] = 8.00

Pile tip resistance (according to DIN 4014 Table 1)
Reduction of pile tip resistance to       SPabmin [-]     = 0.60
s/Df = 0.02                               Sig     [MN/m2] = 0.34
s/Df = 0.03                               Sig1    [MN/m2] = 0.43
s/Df = 0.10                               SigGR   [MN/m2] = 0.96


Internal results
Skin friction:
--------------------------------------------------------------
Layer      Layer  Penetration  Undrainage      Skin  Friction
  No.  thickness   resistance    cohesion  friction     force
                                  of soil
    I         L1           qs          Cu       Tau       Qrg
  [-]        [m]      [MN/m2]     [MN/m2]   [MN/m2]      [MN]
--------------------------------------------------------------
    1      15.00         2.50       -----      0.02     1.434
--------------------------------------------------------------
Sum of friction forces            Qrf          [MN] = 1.434

Load on pile head                 Qma+Qsp = Qv [MN] = 0.500
Skin friction part from Qv        Qma          [MN] = 0.454
End bearing part from Qv          Qsp          [MN] = 0.046
Expected settlement               sv           [cm] = 0.39
```

Pile resistance depending on pile settlement:

No. I [-]	Referred settlement s/Df [-]	Pile head settlement s [cm]	Pile friction resistance Qr [MN]	Tip resistance Qs [MN]	Pile resistance Q [MN]
1	0.01	1.22	1.434	0.145	1.579
2	0.02	1.80	1.434	0.214	1.648
3	0.03	2.70	1.434	0.275	1.709
4	0.10	9.00	1.434	0.611	2.045 = Qg=2*Qzul

```
Final results:
Allowable settlement        Szul              [cm] = 0.79
Allowable pile load         Qr+Qs = Qzul      [MN] = 1.022
Skin friction part          Qr                [MN] = 0.929
End bearing part            Qs                [MN] = 0.094
Safety factor               Qzul/QV = ETHA [-]  = 2.04
```



Load settlement curve of pile according to DIN 4014

Ingenieurgemeinschaft G. Huber / R. Schulze Bachstrasse 12 in D-899 Neutal * Tel. 09262.9999	
Scale: 26	**Project: Pile wall**
File: Pile Wall	**Date: 11_06_2015**
Page No.:	**Title: Bearing capacity and settlement of a pile wall**

1.7.5 Example 4: Bearing capacity of a single pile (EA-Piles)

1.7.5.1 Description of the problem

The bearing capacity of a single pile is required to be determined by the program *GEO Tools* according to "EA-Piles". The same pile example, which can also be found in the Appendix B of DIN 4014 is chosen. Figure 13 summarized the information relating to the soil type, soil strength and pile geometry required for determining the ultimate load capacity of the pile Q (s).

In Figure 13 (example taken from DIN 4014:1990-03) summarizes the information on soil type, ground strength and pile geometry necessary for the determination of the axial pile resistance $R_{c,k}(s)$ based on empirical data.

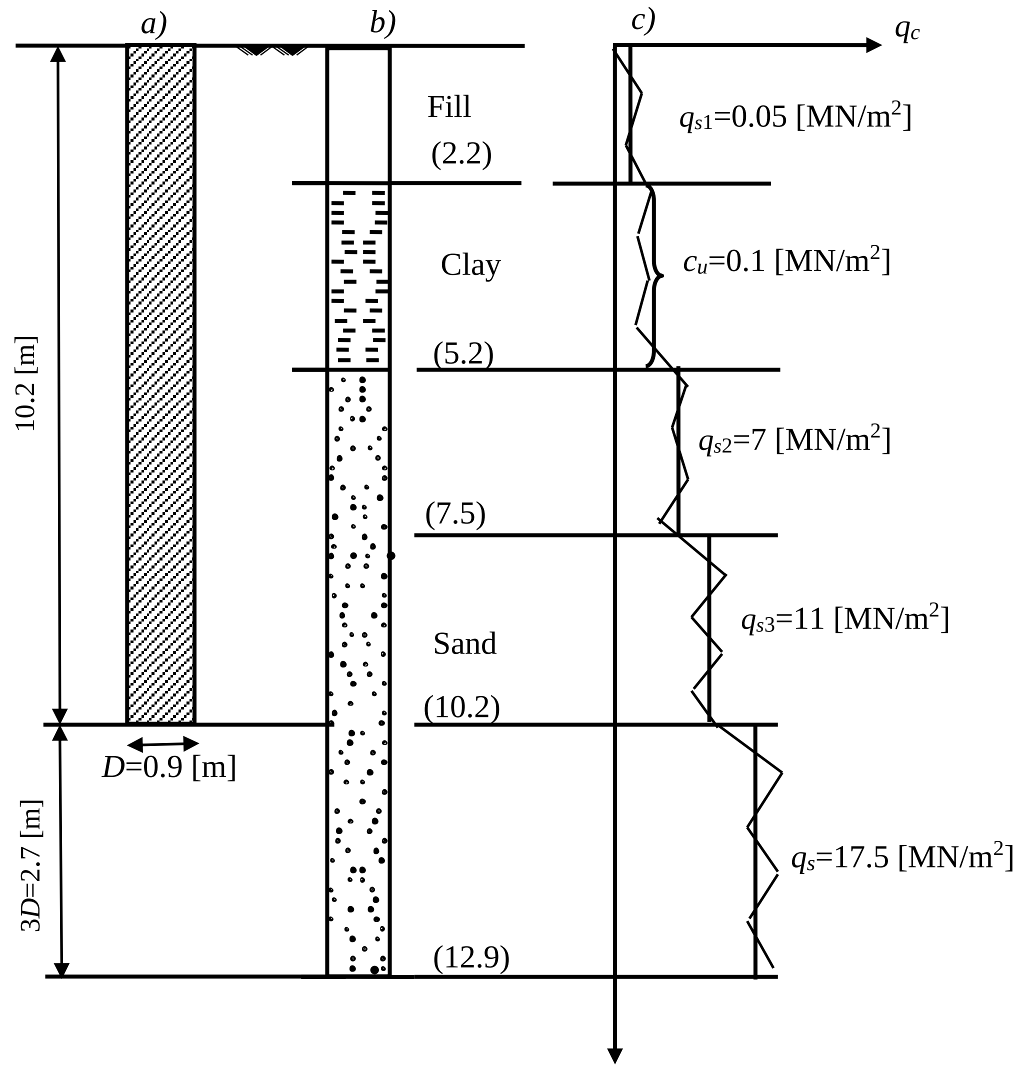


Figure 13 Soil profile, penetration test diagram and dimensions for an example calculation of the resistance-settlement curve; D=0,9 [m], U=2,83 [m], A=0,64 [m^2]

The characteristic resistance-settlement curve shall be determined using the table data after 5.4.6 of "EA-Piles" (Tables 5.12 to 5.15).

1.7.5.2 Analysis for lower and upper table values

Note: Reference is made to the application principles and limitations in 5.4.3 of "EA-Piles", in particular with regard to the upper table values. In the example presented here both the lower and the upper table values are used as examples (not as a rule).

1.7.5.3 Determining the pile shaft resistance $R_{s,k}$

The ultimate limit state skin friction values for the sand and the clay are given in Tables 5.13 and 5.15 in 5.4.6.2 of "EA-Piles". By adopting the associated pile skin areas, the ultimate limit state pile shaft resistances $R_{s,k,i}$ are provided in Table 19.

The settlement s_{sg} in [cm] is calculated as follows, adopting the ultimate limit state pile shaft resistance $R_{s,k}$ in [MN]:

$s_{sg} = 0{,}50 \times R_{s,k} + 0{,}50$

The pile head settlement is:

$s_{sg} = 0{,}50 \times 1{,}243 + 0{,}50 = 1{,}1$ [cm] for the lower table values and
$s_{sg} = 0{,}50 \times 1{,}726 + 0{,}50 = 1{,}4$ [cm] for the upper table values.

Table 19 Ultimate pile shaft resistance for the lower and upper table values

Stratum i [m]	$A_{s,i}$ [m²]	$c_{u,k,i}$ bzw. $q_{c,i}$ [MN/m²]	$q_{s,k,i}$ [MN/m²]	$R_{s,k,i}$ [MN]
2,20 bis 5,20	8,48	0,10	0,039–0,051	0,331–0,432
5,20 bis 7,70	7,07	7,00	0,051–0,075[a)]	0,361–0,530
7,70 bis 10,20	7,07	11,00	0,078–0,108	0,551–0,764
[a)] Extrapolated data				$R_{s,k}$ = 1,243–1,726 [MN]

1.7.5.4 Determining the pile base resistance $R_{b,k}$

A mean soil strength is adopted in a region from 1×D (0,9 m) above and 3×D (3×D=2,70 m) below the pile base to determine $R_{b,k}$. For this zone a mean cone resistance $q_{c,m}$=17,5 [MN/m²] is shown in the penetration test diagram in Figure 13.

The pile base capacity can be calculated by adopting the figures from Table 5.12 in 5.4.6.2 of "EA-Piles" and taking the previously determined value of $q_{c,m}$ into consideration. Table 20 reproduces the calculated figures.

Table 20 Pile base resistance for the lower and upper table values

Relative settlement *s/D*	$q_{b,k}$ [MN/m²]	$R_{b,k(s)}$ [MN]
0,02	1,225–1,625	0,784–1,040
0,03	1,575–2,088	1,008–1,336
0,10	3,250–4,325	2,080–2,768

1.7.5.5 Characteristic resistance-settlement curve

The pile resistances calculated from the pile base and pile shaft resistances are listed in Table 21 and Table 22 as a function of the pile head settlement and are given for the lower and upper values. The settlement of the pile head for each value of the pile resistance $R_{c,k}$ is given by the characteristic resistance settlement curve in Figure 14 and Figure 15.

Table 21 Pile resistance as a function of pile head settlement (lower values)

Relative settlement *s/D*	Pile head settlement [cm]	$R_{s,k(s)}$ [MN]	$R_{b,k(s)}$ [MN]	$R_{c,k(s)}$ [MN]
s_{sg}	1,1	1,243	0,479	1,722
0,02	1,8	1,243	0,784	2,027
0,03	2,7	1,243	1,008	2,251
0,10	9,0	1,243	2,080	3,323

Table 22 Pile resistance as a function of pile head settlement (upper values)

Relative settlement *s/D*	Pile head settlement [cm]	$R_{s,k(s)}$ [MN]	$R_{b,k(s)}$ [MN]	$R_{c,k(s)}$ [MN]
s_{sg}	1,4	1,726	0,809	2,535
0,02	1,8	1,726	1,040	2,766
0,03	2,7	1,726	1,336	3,062
0,10	9,0	1,726	2,768	4,494

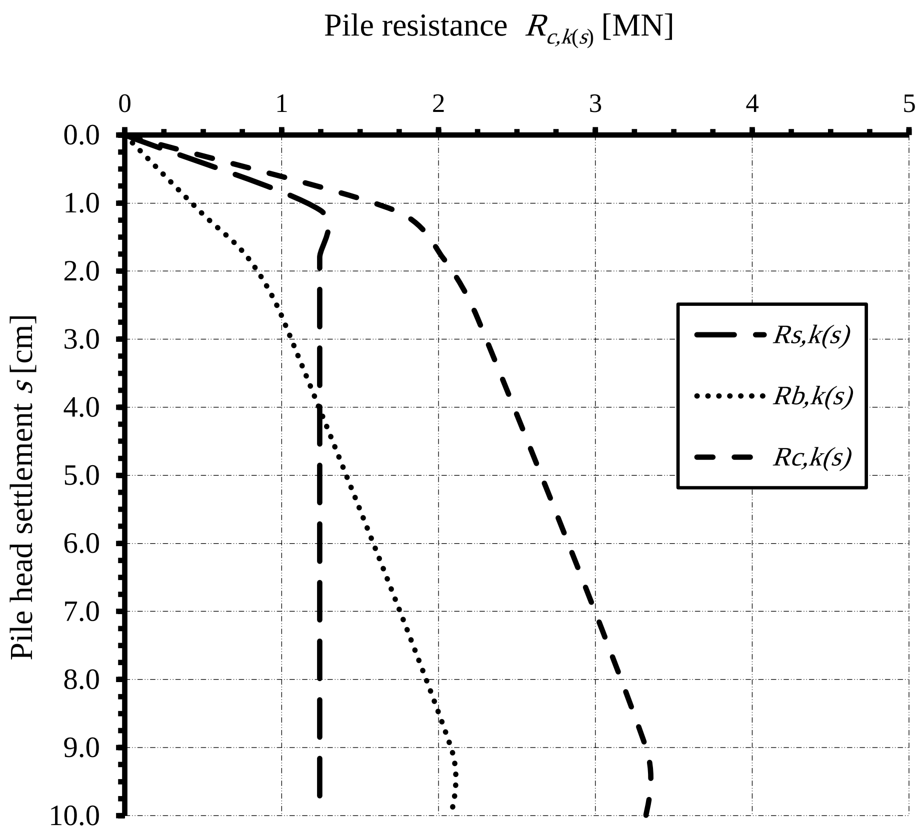


Figure 14 Resistance-settlement curve (lower values) "EA-Piles"

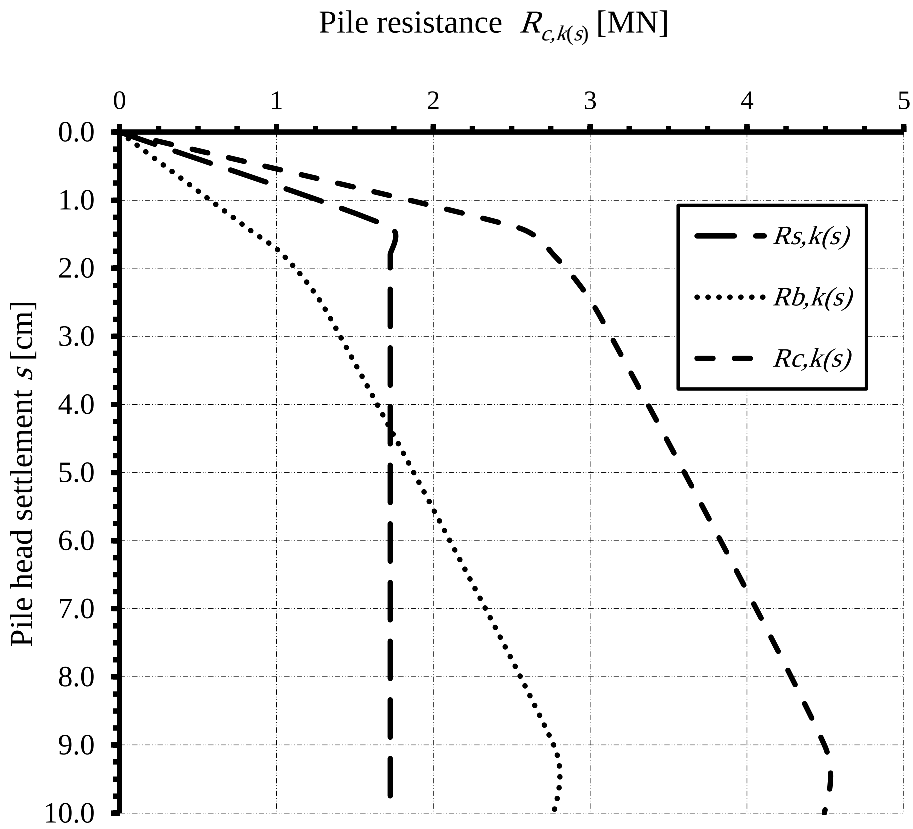


Figure 15 Resistance-settlement curve (upper values) "EA-Piles"

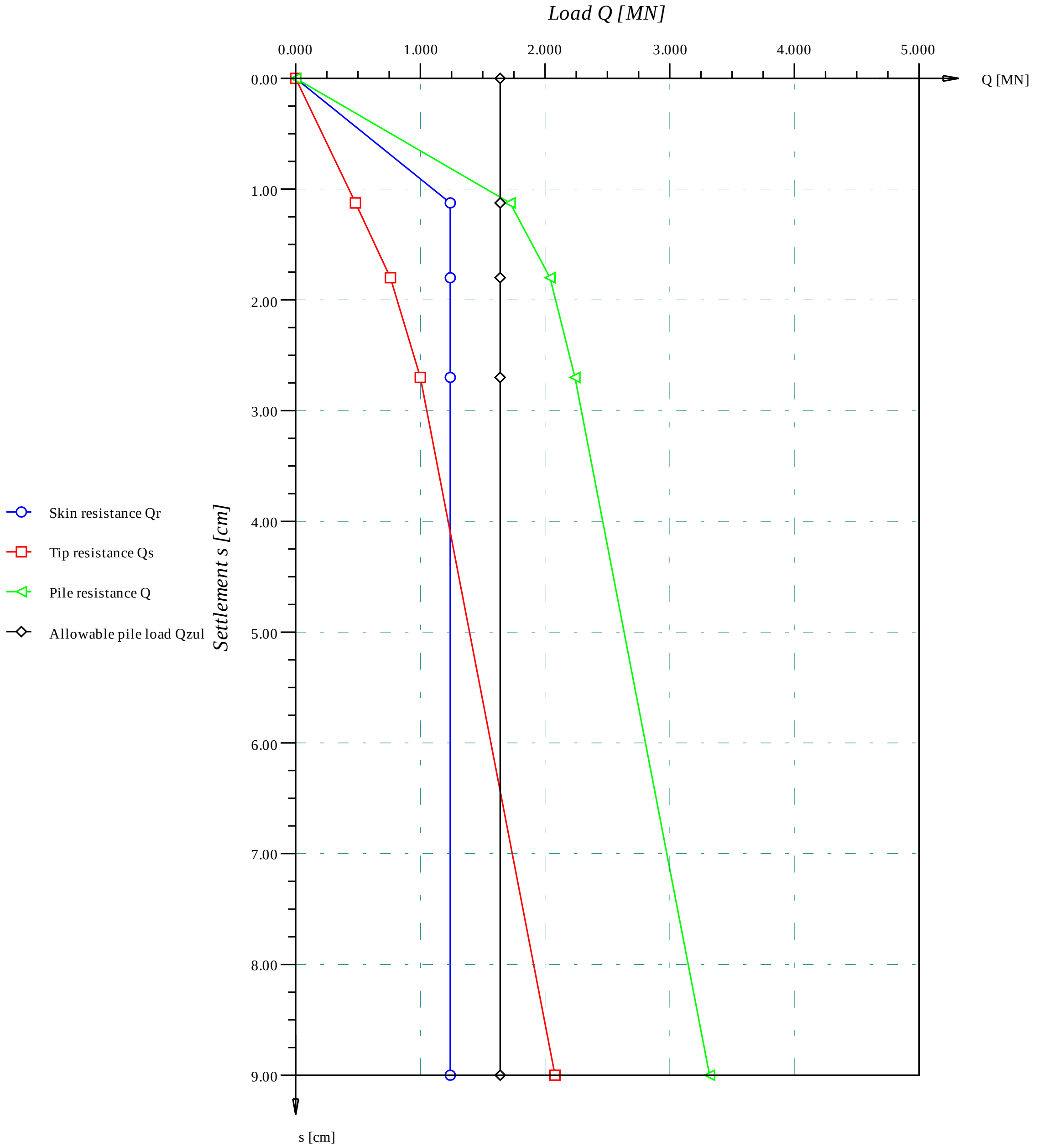
1.7.5.5.1 Computer calculation

The input data and results of *GEO Tools* are presented on the next pages. For each calculation of lower and upper table values there are two pages of input data, intermediate and final results as well as a page of color diagram. By comparison, one can see a good agreement with hand calculation of "EA-Piles".

```
*************************************************************
                        GEO Tools
                         Version 10
     Program authors Prof. M. El Gendy/ Dr. A. El Gendy
*************************************************************
Title: Bearing capacity and settlement of a single pile
Date: 11_06_2015
Project: Example in Appendix B of DIN 4014 after EA-Piles
File: EA-Piles

-------------------------------------------------------------
Bearing capacity and settlement of a single pile
Load settlement curve of pile according to EA-Piles for lower table values
-------------------------------------------------------------

Data:
Pile diameter                               D     [m]     = 0.90
Pile toe diameter                           Df    [m]     = 0.90
Pile length                                 Lg    [m]     = 8.00
Pile label                                  Pz    [-]     = P1
Pile No.                                    Ipf=  [-]     = 1


Summary of results
Soil data under the pile tip:
Penetration resistance under the pile tip  qs    [MN/m2] = 17.50

Pile tip resistance (according to EA-Piles Table 5.12)
s/Df = 0.02                                 Sig   [MN/m2] = 1.23
s/Df = 0.03                                 Sig1  [MN/m2] = 1.58
s/Df = 0.10                                 SigGR [MN/m2] = 3.25


Internal results
Skin friction:
--------------------------------------------------------------
Layer      Layer  Penetration  Undrainage      Skin  Friction
  No.  thickness   resistance    cohesion  friction     force
                                  of soil
    I         L1           qs          Cu       Tau       Qrg
  [-]        [m]      [MN/m2]     [MN/m2]   [MN/m2]      [MN]
--------------------------------------------------------------
    1       3.00         ----       0.100      0.04     0.330
    2       2.50         7.00       -----      0.05     0.363
    3       2.50        11.00       -----      0.08     0.554
--------------------------------------------------------------
Sum of friction forces           Qrf          [MN] = 1.246

Load on pile head                Qma+Qsp = Qv [MN] = 0.800
Skin friction part from Qv       Qma          [MN] = 0.575
End bearing part from Qv         Qsp          [MN] = 0.225
Expected settlement              sv           [cm] = 0.52
```

```
Pile resistance depending on pile settlement:
-----------------------------------------------------------------
No.    Referred          Pile         Pile          Tip         Pile
     settlement          head     friction   resistance   resistance
                   settlement   resistance
  I        s/Df             s           Qr           Qs            Q
[-]         [-]          [cm]         [MN]         [MN]         [MN]
-----------------------------------------------------------------
  1        0.01          1.12        1.246        0.486        1.733
  2        0.02          1.80        1.246        0.779        2.026
  3        0.03          2.70        1.246        1.002        2.248
  4        0.10          9.00        1.246        2.068        3.314 = Qg=2*Qzul
-----------------------------------------------------------------

Final results:
Allowable settlement        Szul             [cm] = 1.07
Allowable pile load         Qr+Qs = Qzul     [MN] = 1.657
Skin friction part          Qr               [MN] = 1.192
End bearing part            Qs               [MN] = 0.465
Safety factor               Qzul/QV = ETHA [-]  = 2.07
```

Pile label: P1
Pile No.: 1



Load settlement curve of pile according to EA-Piles for lower table values

Ingenieurgemeinschaft G. Huber / R. Schulze Bachstrasse 12 in D-899 Neutal * Tel. 09262.9999	
Scale: 40	**Project: Example in Appendix B of DIN 4014 after EA-Piles**
File: EA-Piles	**Date: 11_06_2015**
Page No.:	**Title: Bearing capacity and settlement of a single pile**

```
************************************************************
                        GEO Tools
                         Version 10
     Program authors Prof. M. El Gendy/ Dr. A. El Gendy
************************************************************
Title: Bearing capacity and settlement of a single pile
Date: 11_06_2015
Project: Example in Appendix B of DIN 4014 after EA-Piles
File: EA-Piles

------------------------------------------------------------
Bearing capacity and settlement of a single pile
Load settlement curve of pile according to EA-Piles for upper table values
------------------------------------------------------------

Data:
Pile diameter                               D     [m]     = 0.90
Pile toe diameter                           Df    [m]     = 0.90
Pile length                                 Lg    [m]     = 8.00
Pile label                                  Pz    [-]     = P1
Pile No.                                    Ipf=  [-]     = 1


Summary of results
Soil data under the pile tip:
Penetration resistance under the pile tip  qs    [MN/m2] = 17.50

Pile tip resistance (according to EA-Piles Table 5.12)
s/Df = 0.02                                 Sig   [MN/m2] = 1.63
s/Df = 0.03                                 Sig1  [MN/m2] = 2.09
s/Df = 0.10                                 SigGR [MN/m2] = 4.33


Internal results
Skin friction:
-------------------------------------------------------------
Layer      Layer  Penetration  Undrainage      Skin  Friction
  No.  thickness   resistance    cohesion  friction     force
                                  of soil
    I         L1           qs          Cu        Tau       Qrg
  [-]        [m]      [MN/m2]     [MN/m2]   [MN/m2]      [MN]
-------------------------------------------------------------
    1       3.00         ----       0.100       0.05     0.434
    2       2.50         7.00       -----       0.07     0.528
    3       2.50        11.00       -----       0.11     0.763
-------------------------------------------------------------
Sum of friction forces           Qrf          [MN] = 1.725

Load on pile head                Qma+Qsp = Qv [MN] = 0.800
Skin friction part from Qv       Qma          [MN] = 0.550
End bearing part from Qv         Qsp          [MN] = 0.250
Expected settlement              sv           [cm] = 0.43
```

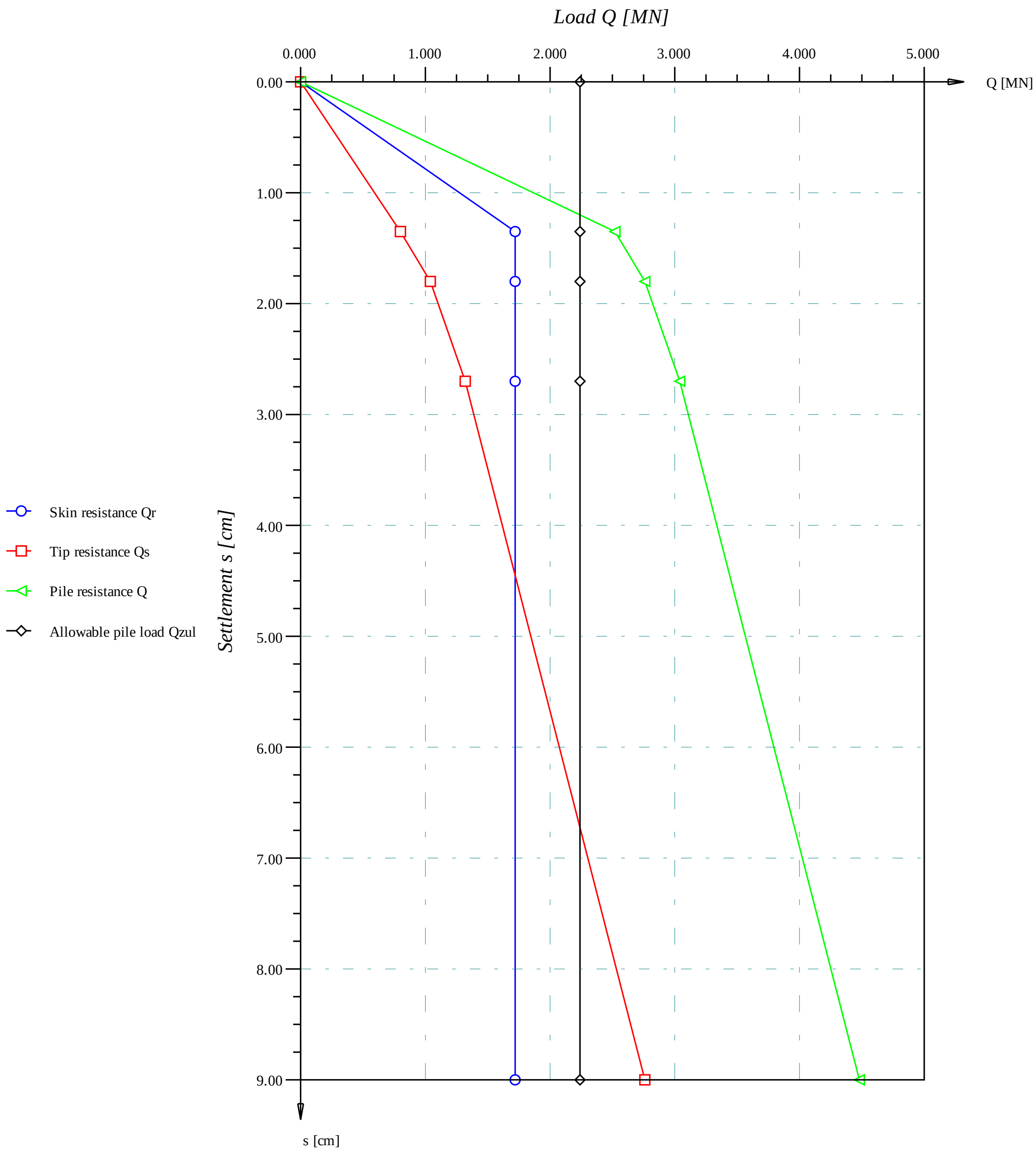
Pile resistance depending on pile settlement:

No.	Referred settlement	Pile head settlement	Pile friction resistance	Tip resistance	Pile resistance	
I	s/Df	s	Qr	Qs	Q	
[-]	[-]	[cm]	[MN]	[MN]	[MN]	
1	0.02	1.36	1.725	0.782	2.507	
2	0.02	1.80	1.725	1.034	2.759	
3	0.03	2.70	1.725	1.328	3.053	
4	0.10	9.00	1.725	2.751	4.476	= Qg=2*Qzul

```
Final results:
Allowable settlement        Szul             [cm] = 1.22
Allowable pile load         Qr+Qs = Qzul     [MN] = 2.238
Skin friction part          Qr               [MN] = 1.540
End bearing part            Qs               [MN] = 0.698
Safety factor               Qzul/QV = ETHA [-]  = 2.80
```

Pile label: P1

Pile No.: 1



Load settlement curve of pile according to EA-Piles for upper table values

Ingenieurgemeinschaft G. Huber / R. Schulze Bachstrasse 12 in D-899 Neutal * Tel. 09262.9999	
Scale: 40	**Project: Example in Appendix B of DIN 4014 after EA-Piles**
File: EA-Piles	**Date: 11_06_2015**
Page No.:	**Title: Bearing capacity and settlement of a single pile**

1.7.6 Example 5: Bearing capacity of a single pile (ECP)

1.7.6.1 Description of the problem

It is required to analyze a single bored pile used to support a pile cap of a bridge. The analysis of the single pile was carried out by the program *GEO Tools* to chose the suitable pile diameter by evaluating the load-settlement behavior of the pile. The load-settlement relation is determined according to *ECP* 197 (1995) for bored piles of diameters greater than 60 [cm].

1.7.6.2 Soil properties

The subsoil at the location of the bridge consists of variable layers of sand and clay with different properties up to a depth of 25 [m] under the sea bed level. Main soil data obtained from boreholes located in the position of the piles are presented in Table 23.

Table 23 Soil property

Layer	Layer Depth Under the SBL [m]	Soil Type	Av. SPT N Value	Angle of Int. friction Φ [°]	Undrainage cohesion c_u [kN/m²]
1	0.0-3.0	CL-ML	1	-	50
2	3.0-7.5	SM	30	35	-
3	7.5-12.0	GM	>100	38	-
4	12.0-15.0	SM	28	35	-
5	15.0-18.0	CL	38	-	150
6	18.0-22.5	SC-SM	48	31	-
7	22.5-25.0	CL	>100	-	250

1.7.6.3 Choosing pile diameter and design load

The design load for the single pile for the considered diameter is chosen to meet a maximum settlement of 1.0 [cm]. Consideration is given also to using a wider pile in diameter to develop bearing loads in less number of piles. Accordingly, a pile of diameter 1.4 [m] and length of 28 [m] is chosen. The design load for the chosen pile is about 2.5 [MN]. Due to the group action, the settlement of the chosen pile in the pile group is expected to be higher than that obtained from the single pile analysis.

1.7.6.4 Estimation of pile skin friction

ECP requires to estimate the skin friction resistance according to the tables presented in the code using either soil data *SPT* for non-cohesive soil or cohesion c_u for cohesive soil. The estimation of friction resistances for non-cohesive soil is presented in Table 24, while that for cohesive soil is presented in Table 25

Table 24 Estimation of pile skin friction for non-cohesive soil

Layer	Soil Type	Layer Depth Under the SBL [m]	Av. *SPT* N Value	Values according ECP (1995)		
				depth	*SPT*	Skin friction τ [kN/m^2]
2	SM	3.0-7.5	30	2.0-7.5	20.0-30.0	45
3	GM	7.5-12.0	>100	2.0-10.0	>30.0	60
4	SM	12.0-15.0	28	>7.5	20.0-30.0	75
6	SC-SM	18.0-22.5	48	>10.0	>30.0	100

Table 25 Estimation of pile skin friction for cohesive soil

Layer	Soil Type	Layer Depth Under the SBL [m]	Undrainage cohesion c_u [kN/m^2]	Values according ECP (1995)	
				Undrainage cohesion c_u [kN/m^2]	Skin friction τ [kN/m^2]
1	CL-ML	0.0-3.0	50	50	35
5	CL	15.0-18.0	150	150	45
7	CL	22.5-25.0	250	250	50

1.7.6.5 Results

The summary of the single pile analysis is listed in Table 26. Input and output results from *GEO Tools* are presented in the next two pages besides a color diagram for load settlement relation.

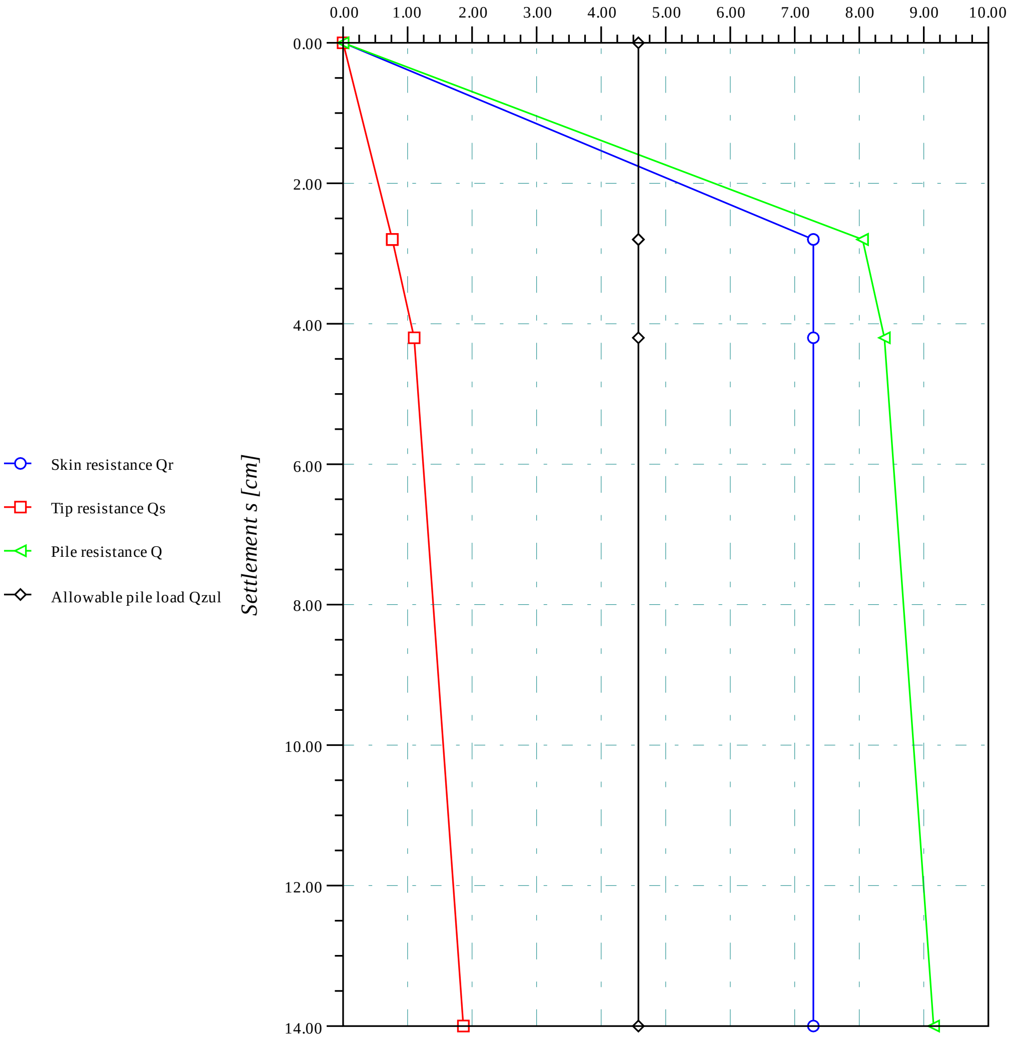
Table 26 Pile load and settlemen

Pile diameter *d* [m]	Pile length *Lp* [m]	Allowable pile load Q_{all} [MN]	Allowable pile settlement S_{all} [cm]	Design pile load Q_v [MN]	Expected settlement S_e [cm]
1.4	28	4.58	1.69	2.5	0.87

```
**********************************************************
                    GEO Tools
                     Version 10
     Program authors Prof. M. El Gendy/ Dr. A. El Gendy
**********************************************************
Title: Bearing capacity of a single pile
Date: 25/09/2010
Project: ECP
File: ECP

----------------------------------------------------------
Bearing capacity and settlement of a single pile
Load settlement curve of Piles is defined by the user
----------------------------------------------------------

Data:
Pile diameter            D     [m]     = 1.4
Pile toe diameter        Df    [m]     = 1.4
Pile length              Lg    [m]     = 28.0
Pile label               Pz    [-]     = P1
Pile No.                 Ipf=  [-]     = 1


Summary of results

Pile tip resistance (Given)
s/Df = 0.02              Sig   [MN/m2] = 0.5000
s/Df = 0.03              Sig1  [MN/m2] = 0.7000
s/Df = 0.10              SigGR [MN/m2] = 1.2000


Internal results
Skin friction:
-----------------------------------------------------------
Layer     Layer  Penetration  Undrainage     Skin  Friction
  No. thickness          tip    cohesion  friction     force
          resistance   of soil
    I        L1           qs          Cu       Tau       Qrg
  [-]       [m]      [MN/m2]     [MN/m2]   [MN/m2]      [MN]
-----------------------------------------------------------
    1       3.0       ------      ------    0.0350      0.46
    2       4.5       ------      ------    0.0450      0.89
    3       4.5       ------      ------    0.0600      1.19
    4       3.0       ------      ------    0.0750      0.99
    5       3.0       ------      ------    0.0450      0.59
    6       4.5       ------      ------    0.1000      1.98
    7       5.5       ------      ------    0.0500      1.21
-----------------------------------------------------------
Sum of friction forces           Qrf           [MN] = 7.31

Load on pile head                Qma+Qsp = Qv  [MN] = 2.50
Skin friction part from Qv       Qma           [MN] = 2.26
End bearing part from Qv         Qsp           [MN] = 0.24
Expected settlement              sv            [cm] = 0.87
```

```
Pile resistance depending on pile settlement:
-----------------------------------------------------------------
No.    Referred         Pile         Pile          Tip        Pile
     settlement         head     friction   resistance  resistance
                  settlement   resistance
  I       s/Df            s           Qr           Qs           Q
[-]        [-]         [cm]         [MN]         [MN]        [MN]
-----------------------------------------------------------------
  1      0.020         2.80         7.31         0.77        8.08
  2      0.020         2.80         7.31         0.77        8.08
  3      0.030         4.20         7.31         1.08        8.39
  4      0.100        14.00         7.31         1.85        9.16 = Qg=2*Qzul
-----------------------------------------------------------------

Final results:
Allowable settlement        Szul            [cm] = 1.59
Allowable pile load         Qr+Qs = Qzul    [MN] = 4.58
Skin friction part          Qr              [MN] = 4.14
End bearing part            Qs              [MN] = 0.44
Safety factor               Qzul/QV = ETHA  [-]  = 1.832
```

Pile label: P1
Pile No.: 1



Load settlement curve of Piles is defined by the user

Ingenieurgemeinschaft G. Huber / R. Schulze Bachstrasse 12 in D-899 Neutal * Tel. 09262.9999	
Scale: 85	Project: ECP
File: ECP	Date: 25/09/2010
Page No.:	Title: Bearing capacity of a single pile

1.8 References

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