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GEO5

Engineering manuals

Part 2

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Engineering manuals for GEO5 programs

Part 2

Chapter 1 - 12, refer to Engineering Manual Part 1

Chapter 13. Pile Foundations – Introduction 2

Chapter 14. Analysis of vertical load-bearing capacity of a single pile..... 10

Chapter 15. Analysis of a single pile settlement 22

Chapter 16. Analysis of vertical load-bearing capacity and settlement of piles investigated on the basis of CPT tests..... 32

Chapter 17. Analysis of horizontal bearing capacity of a single pile..... 41

Chapter 18. Analysis of vertical load bearing capacity and settlement of a pile group 49

Chapter 19. Analysis of deformation and pile group dimensioning..... 57

Chapter 13. Pile Foundations – Introduction

The objective of this chapter is to explain the practical use of programs for the analysis of pile foundations in GEO 5.

GEO 5 software contains three pile foundation analysis programs – ***Piles, Pile CPT and Pile Group***. The text below contains closer explanation of which of the programs is to be used under particular conditions – individual programs are subsequently described in other chapters.

Vertical load-bearing capacity of pile foundations is determined by various methods:

- ***by a static pile test***: these tests are directly required in some countries and a structural analysis functions only as a preliminary pile foundation proposal;

- ***by an analysis based on soil shear strength parameters:*** using analysis methods NAVFAC DM 7.2, Tomlinson, CSN 73 1002 and Effective stress in programs PILES and PILE GROUP;

- ***by an analysis based on the assessment of penetration tests:*** PILE CPT program;

- ***by an analysis according to equations for regression curves obtained from the results of static loading tests*** (according to Masopust): PILES program; Vertical load-bearing capacity is determined from the pile loading curve for corresponding (allowable) settlement (CSN 73 1002 standard specifies the corresponding settlement value $s_{\lim} = 25.0\ mm$).

- ***by an analysis based on Mohr-Coulomb parameters and stress-strain properties of soils***: using the so-called Spring Method in PILES and PILE GROUP programs;

- ***by numerical analysis using the Finite Element Method***: the FEM program.

It follows from this list that piles can be assessed using many ways and on the basis of different input parameters. It means that analysis results can be identical, but often they can significantly differ.

The great advantage of GEO 5 is the fact that the user can try more variants and analysis methods, find the most likely behaviour of the pile foundation and subsequently determine the total bearing capacity or settlement of a single pile or a pile group.

The vertical load-bearing capacity of pile foundations is assessed in GEO 5 programs (with the only exception: Pile Group – Spring Method) only for the loading by a vertical normal force. The loading by horizontal forces, bending and torsional moments has no influence on the analysis of the vertical load-bearing capacity of piles.

The procedure of the vertical load-bearing capacity of a single pile analysis in GEO 5 – PILES is presented in *Chapters 14* and *15*, whilst the analysis for the same pile on the basis of CPT tests is described in *Chapter 16*.

Horizontal bearing capacity of pile foundations:
The result of the analysis for a horizontally loaded pile is the pile horizontal deformation and the curve for internal forces along the pile shaft.

In the case of a single pile, its horizontal deformation and reinforcement depend on the calculated modulus of horizontal reaction of the sub-soil and the loading by the lateral force or the bending moment. The analysis procedure is explained in *Chapter 17*. The analysis for a pile group is presented in *Chapter 19*.

Settlement of pile foundations:
The actual load-bearing capacity of a pile is directly associated with its settlement because of the fact that virtually any pile settles under the action of loading and gets vertically deformed.

The settlement of single piles is determined in the PILES program by the following methods:

- ***according to Masopust*** (non-linear): the program analyses the settlement of a single pile on the basis of the regression coefficients along the skin and under the pile base.

- ***according to Poulos*** (linear): the program analyses the value of the total settlement on the basis of the determined pile base bearing capacity R_b and the pile skin bearing capacity R_s.

– ***by means of the Spring Method***: the program analyses the loading curve on the basis of set parameters of soils using the Finite Element Method.

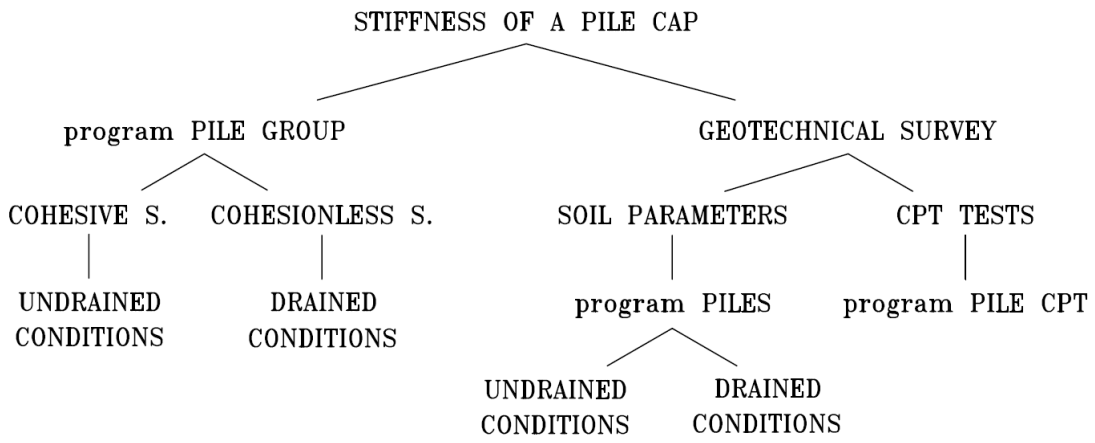
The PILES program constructs the loading curve (the so-called working diagram) for all of the methods.

The settlement of a pile group is described in *Chapter 18*, the settlement of piles designed on the basis of penetration tests CPT is presented in *Chapter 16*.

Program selection:

1. ***the decision*** according to the stiffness of the base slab (pile cap). When the pile cap is considered to be infinitely stiff, the Pile Group solution is used. In the other cases we investigate single piles.

2. ***the decision*** according the results of geological survey. If results of CPT tests are available, the Pile CPT program is used for the analysis of the single pile or the pile group *(see Chapter 16)*. In the other cases the program Piles (or Pile Group) is used for the solution, on the basis of the set soil parameters.



Distinguished according to the ***analysis type*** are:

– analysis for drained conditions: effective parameters of shear strength of soils φ_{ef}, c_{ef} are used in the Piles and Pile Group programs as a standard for analysis methods *CSN 73 1002* and *Effective stress*;

- analysis for undrained conditions: only the value of the total soil cohesion c_u is set in the Piles and Pile Group programs. The vertical load-bearing capacity of a single pile is determined according to *Tomlinson*, whilst a pile group is analysed as the load-bearing capacity of a soil cylinder (block) according to *the FHWA*.

The NAVFAC DM 7.2 method combines both of the above-mentioned analysis procedures. It is possible for each soil layer to choose whether the soil is considered as drained (cohesionless) or undrained (cohesive).

General specification of the problem:

Analyse the vertical load-bearing capacity and settlement of a pile foundation (see the Chart) in the set geological profile; further determine the horizontal deformation of the piles and propose reinforcement for individual piles. The pile foundation consists of four bored piles with the diameter $d = 1.0\ m$ and length $l = 12.0\ m$. The resultant of the total loading N, M_y, H_x acts at the level of the upper surface of the foundation slab (pile cap) namely in the slab centre. C 20/25 reinforced concrete is used for the piles.

Loads acting on piles:

For the problem simplification we will always consider 1 loading case in the program.

The determination of loads acting on the pile foundation is different depending on the structure type and subsequent solution, i.e. whether we solve a single pile or a pile group.

Pile Group

We assume that the slab joining the piles is stiff. In our case we will consider a pile cap with the thickness $t = 1.0\ m$. In this case we determine the total reaction in the pile cap centre.

Note: A simple method of obtaining loads on a pile group using any of the static programs is described in the Help for the Pile Group program "Determination of loading on a pile group".

a) Design (calculation) loads:

– *Vertical normal force*: $N = 5680\ kN$,

– *Bending moment*: $M_y = 480\ kNm$,

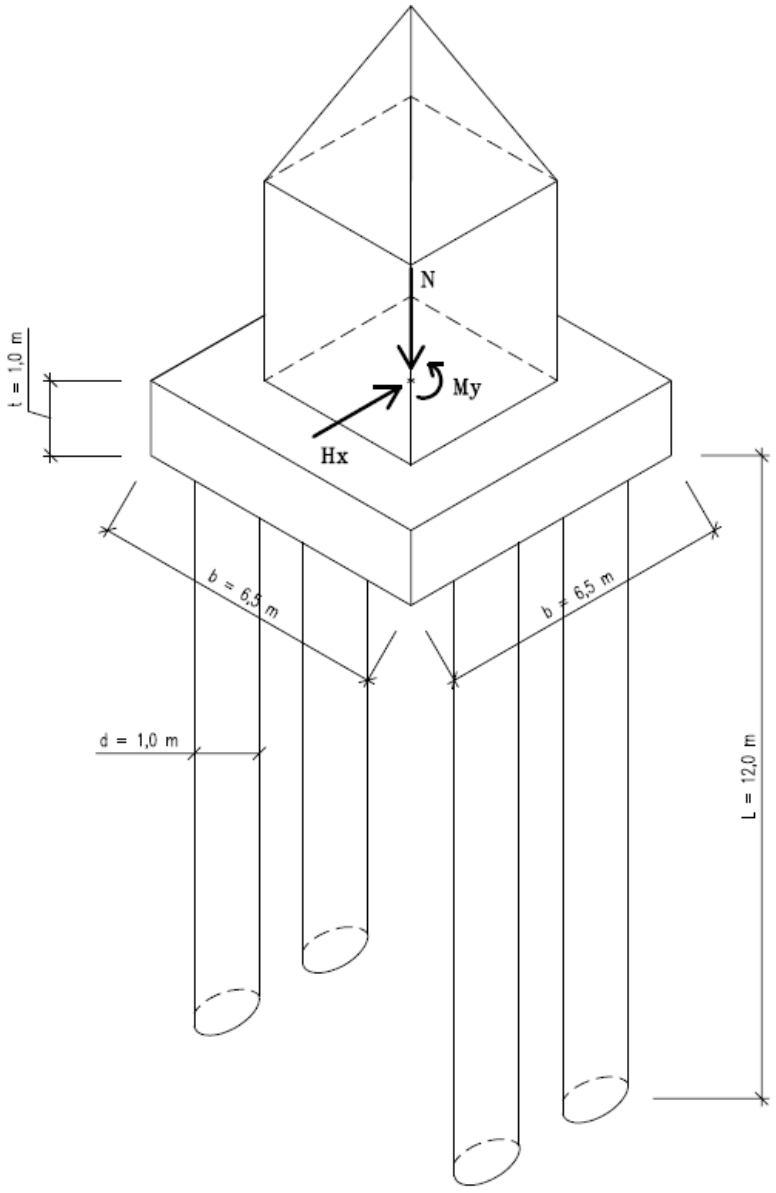
– *Horizontal force* $H_x = 310\ kN$.

b) Imposed (working) loads:

– *Vertical normal force*: $N = 4000\ kN$,

– *Bending moment*: $M_y = 320\ kNm$,

– *Horizontal force*: $H_x = 240\ kN$.



Problem specification chart – pile foundation

Single piles:

If the slab is soft in bending (non-stiff) or the building is founded on a pile cap, the structural diagram is different and we will obtain reactions at the heads of individual piles from a static program (e.g. GEO 5 – Plate, FIN 3D, SCIA Engineer, Dlubal RStab etc.).

In this example, we will for simplification carry out the pile analysis using only 1 loading case.

a) Design loading:

– *Vertical normal force*: $N_1 = 1450\ kN$,

– *Bending moment*: $M_{y,1} = 120\ kNm$,

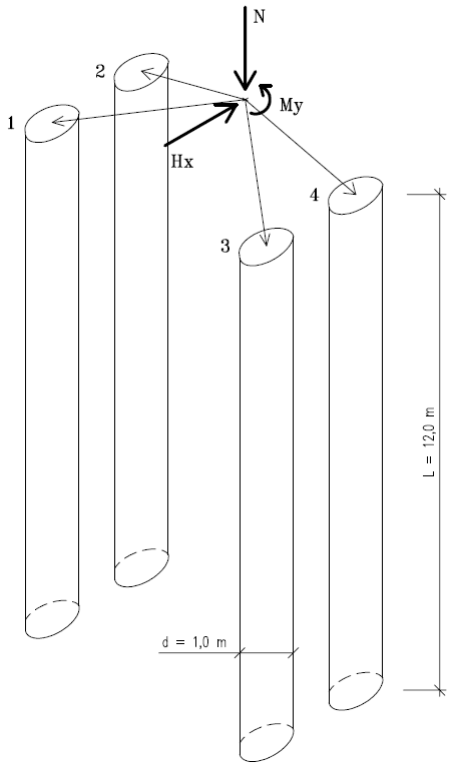
– *Horizontal force*: $H_{x,1} = 85\ kN$.

b) Service loading:

– *Vertical normal force*: $N_1 = 1015\ kN$,

– *Bending moment*: $M_{y,1} = 80\ kNm$,

– *Horizontal force*: $H_{x,1} = 60\ kN$.



Loads action chart – distribution of loading among individual single piles

Note: If we assume identical dimensions and reinforcement of piles, we can assess all piles as one pile, but with loading combinations acting on all piles.

Geological profile

- *0.0 to 6.0 m*: Sandy Clay (CS, consistency firm),
- *down from 6,0 m*: Sand with trace of fines (S-F, medium dense soil).

Note: The basic soil parameters are the same as for the calculation of single piles and for the verification of the pile group. Their values are given in the following table.

Soil parameters / Classification	Sandy Clay (CS) consistency firm	Sand with trace of fines (S-F) medium dense soil
Unit weight $\gamma\ [kN/m^3]$	18,5	17,5
Unit weight of satur. soil $\gamma_{sat}\ [kN/m^3]$	20,5	19,5
Cohesion of soil $c_{ef}\ / c_u\ [kPa]$	14,0 / 50,0	0 / 0
Angle of internal friction $\varphi_{ef}\ [°]$	24,5	29,5
Adhesion factor $\alpha\ [–]$	0,6	–
Bearing capacity coefficient $\beta_p\ [–]$	0,3	0,45
Poisson´s ratio $\nu\ [–]$	0,35	0,3
Oedometric modulus $E_{oed}\ [MPa]$	8,0	21,0
Deformation modulus $E_{def}\ [MPa]$	5,0	15,5
Type of soil	Clay (cohesive soil)	Sand, gravel (cohesionless soil)
Angle of dispersion $\beta\ [–]$	10,0	15,0
Coefficient $k\ [MN/m^3]$	60,0	150,0
Modulus of horizont. comp. $n_h\ [MN/m^3]$	–	4,5
Modulus of elasticity $E\ [MPa]$	5,0	15,5

Table with the soil parameters – pile foundations (summary)

List of chapters related to pile foundations:

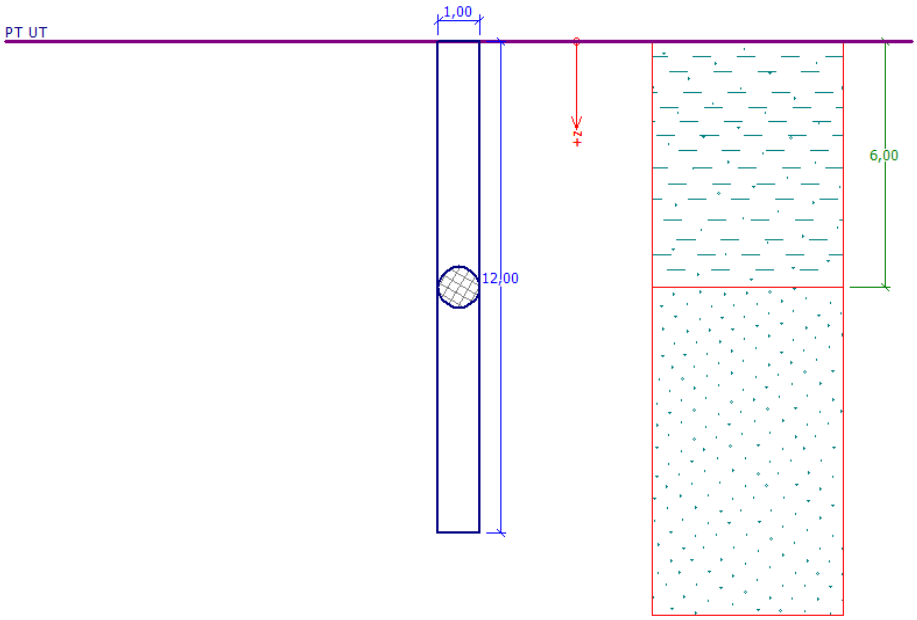
- *Chapter 13*: Pile foundations
- *Chapter 14*: Analysis of vertical load-bearing capacity of a single pile
- *Chapter 15*: Analysis of single pile settlement
- *Chapter 16*: CPT tests based pile analysis
- *Chapter 17*: Analysis of horizontal load-bearing capacity of a single pile
- *Chapter 18*: Analysis of vertical load-bearing capacity and settlement of a pile group
- *Chapter 19*: Analysis of deformation and pile group dimensioning.

Chapter 14. Analysis of vertical load-bearing capacity of a single pile

The objective of this chapter is to explain the application of the GEO 5 – PILES program for the analysis of vertical load-bearing capacity of a single pile to a specified practical problem.

Problem specification:

General problem specification is described in the previous chapter (*13. Pile foundations – Introduction*). All analyses of the vertical load-bearing capacity of a single pile shall be carried out in compliance with requirements of EN 1997-1 (Design approach 2). The resultant of loading components $N_1, M_{y,1}, H_{x,1}$ acts at the pile head level.



Problem specification chart – single pile

Solution:

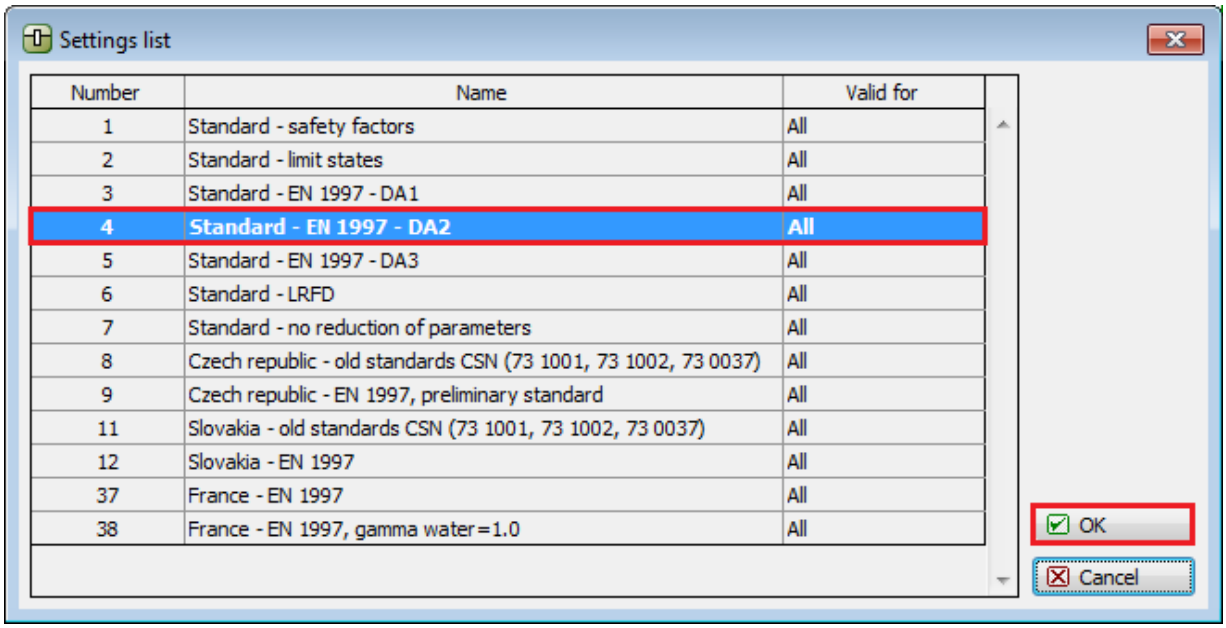
We will apply the GEO 5 – PILES program to the analysis of this problem. In the text below we will describe the solution to this example step by step.

In this analysis we will assess a single pile using various analytical calculation methods (NAVFAC DM 7.2, EFETIVE STRESS and CSN 73 1002) and will focus ourselves on the ***input parameters*** which influence overall results. In new versions of the GEO 5 Piles program there will be more methods available; at the moment (July 2013) the Russian SNiP

and Chinese GB are being worked on. The system of working with the program will remain completely unchanged.

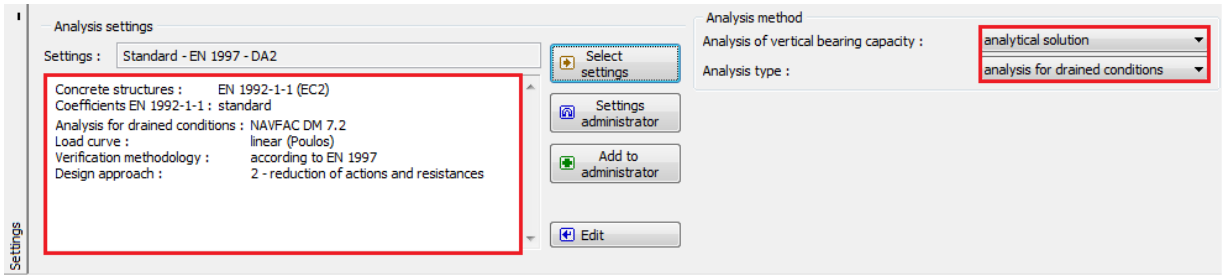
Specification definition:

We click on the Select Settings button (at the bottom left of the screen) in the Settings frame and then we select the "Standard – EN 1997 – DA2" analysis setting. Further we set the method of the analysis of vertical load-bearing capacity of a pile using *the analytical solution.* In our case we will assess the pile in ***drained conditions***.



Dialog window „Setting list"

We will use the NAVFAC DM 7.2 method, which is set by default for this analysis setting, for the initial assessment of the pile (see the *picture*).



Frame „Analysis settings"

In the next step we will specify the geological profile. We will leave the „Modulus k_h“ out, because of the fact that in this analysis we don´t analyse the lateral load. In our case it therefore doesn´t matter which value is specified for the „Dispersion angle β“, because this parameter will not at all affect the resulting value of the vertical load-bearing capacity of the pile.

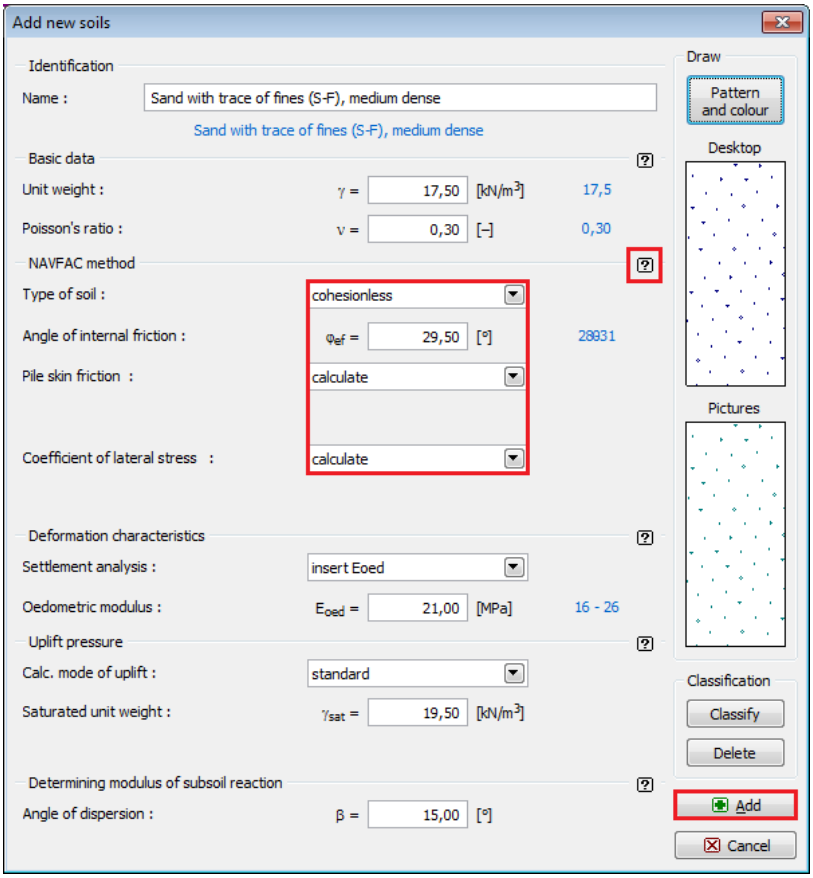
Further we will define the other parameters of soils required for the analysis and assign them to the profile. The **NAVFAC DM 7.2** method requires that the soil type is defined first, i.e. whether it is a cohesive or cohesionless soil layer. All below-listed parameters influence the magnitude of skin friction $R_s\ [kN]$.

Soil (Soil classification)	Unit weight $\gamma\ [kN/m^3]$	Angle of internal friction $\varphi_{ef}\ [°]$	Cohesion of soil $c_{ef}\ /\ c_u\ [kPa]$	Adhesion factor $\alpha\ [–]$	Bearing capacity coefficient $\beta_p\ [–]$
CS – Sandy clay, firm consistency	18.5	24.5	- / 50	0.60	0.30
S-F – Sand with trace of fines, medium dense soil	17.5	29.5	0 / -	-	0.45

Table with the soil parameters – Vertical bearing capacity (analytical solution)

For the 1st layer, which is considered as ***undrained cohesive soil*** (class F4, firm consistency), we must in addition specify the total soil cohesion (undrained shear strength) $c_u\ [kPa]$ and the so-called adhesion factor $\alpha\ [–]$. This factor is determined relative to the soil consistency, pile material and total soil cohesion (for more details visit Help – F1).

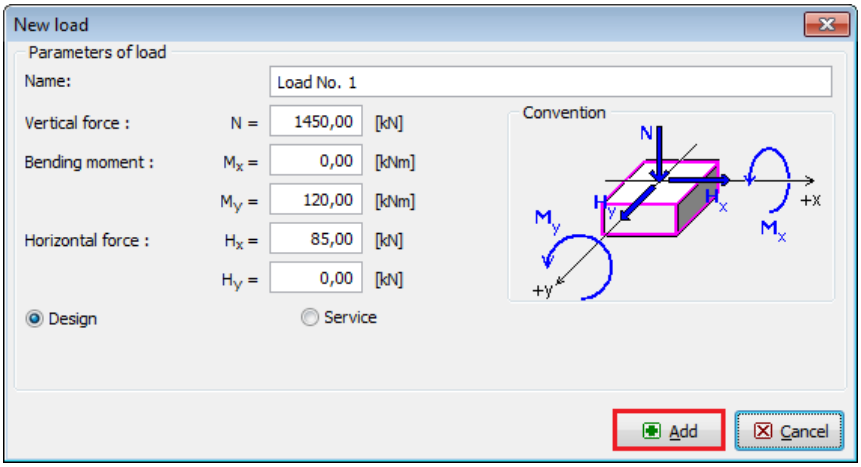
For the 2nd layer, which is considered as ***cohesionless soil*** (class S3, medium dense), we must in addition specify the angle of skin friction $\delta\ [°]$, which depends on the pile material. Further we must define the coefficient of lateral stress $K\ [–]$, which is affected by the type of loading (tension – pressure) and by the pile installation technology (for more details visit Help – F1). For the problem simplification we will select the option „calculate“ for both of the two variants.



Dialogue window „Add new soils“

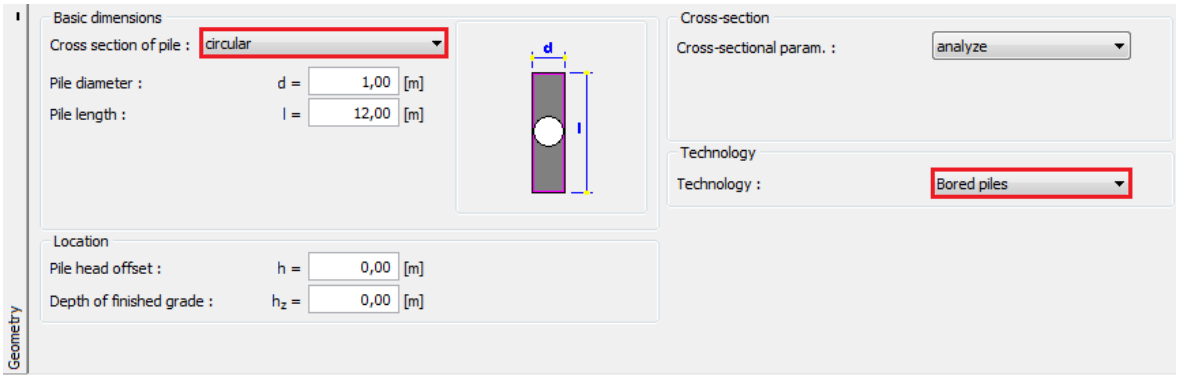
In the “Material” frame, we will specify material characteristics of the pile – unit weight of the structure $\gamma = 23.0\ kN/m^3$.

Subsequently we will define the load acting on the pile. The design (calculation) loading is considered for the calculation of the vertical load-bearing capacity of the pile, while the service load is considered for the calculation of settlement.



Dialogue window „New load“

In the "Geometry" frame we will specify the circular cross-section of the pile and further determine its basic dimensions, i.e. the diameter and length. Subsequently we will define the type of the pile installation technology.



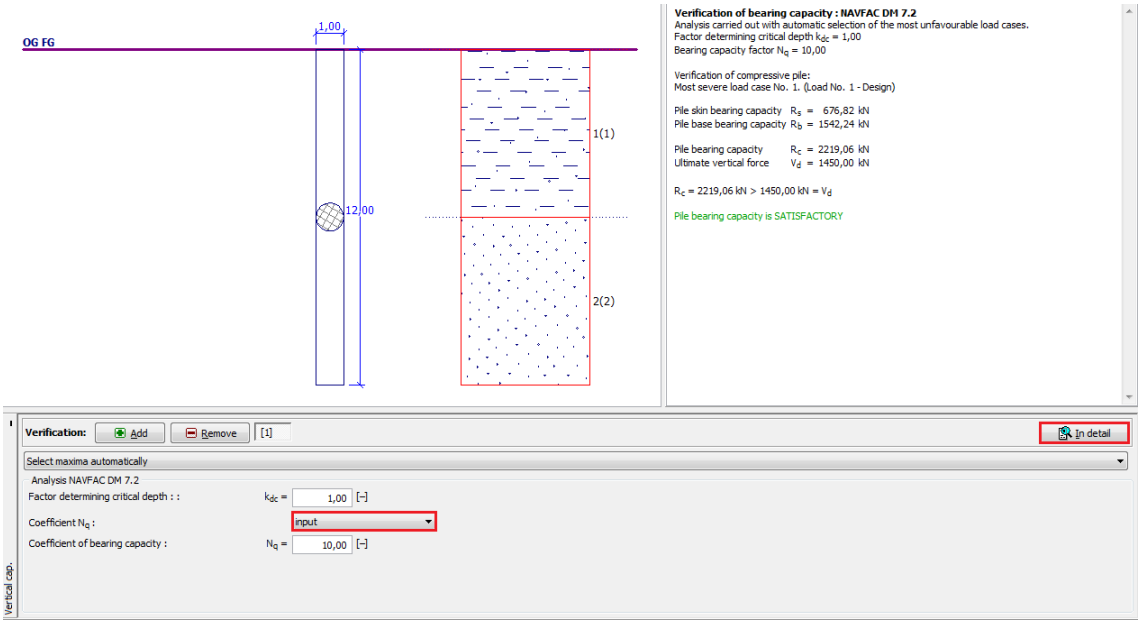
„Geometry" frame

We will leave the "GWT + subsoil" frame out. In the "Stage settings" frame we will leave the permanent design situation and then we will go over to the assessment of the pile using the "Vertical capacity" frame.

Analysis of vertical load-bearing capacity of a single pile – NAVFAC DM 7.2 analysis method

First we must specify in the frame "Vertical capacity" the calculation parameters affecting the magnitude of the pile base bearing capacity $R_b\ [kN]$. First we will define the critical depth $k_{dc}\ [-]$ analysis coefficient, which is derived from the so-called critical depth depending on the soil density (for more details visit Help – F1). We will consider this coefficient as $k_{dc} = 1{,}0$.

Another important parameter is the coefficient of bearing capacity $N_q\ [-]$, which is determined according to the size of the soil internal friction angle $\varphi_{ef}\ [°]$ relative to the pile installation technology (for more details visit Help – F1). In this case we will consider $N_q = 10.0$.



"Vertical capacity" frame – assessment according to NAVFAC DM 7.2"

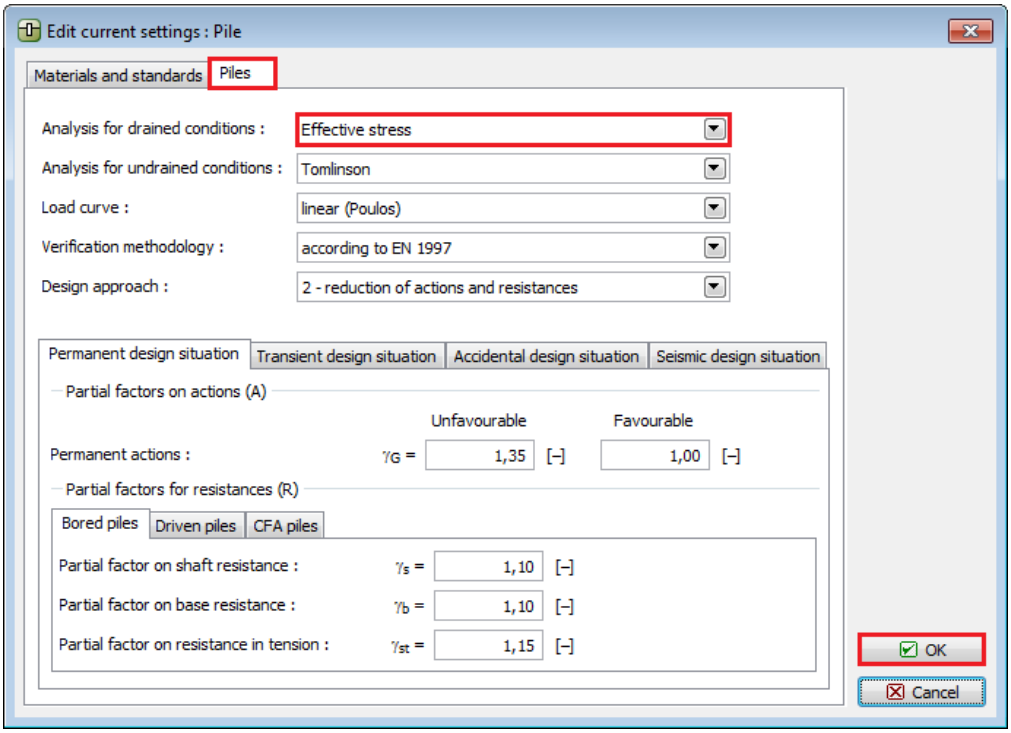
The design vertical bearing capacity of a centrally loaded pile $R_c\ [kN]$ consists of the sum of the skin friction R_s and the resistance on pile base R_b. To meet the condition for reliability, its value must be higher than the magnitude of the design load $V_d\ [kN]$ acting on the pile head.

– **NAVFAC DM 7.2**: $R_c = 2219.06\ kN > V_d = 1450.0\ kN$ … SATISFACTORY.

Analysis of vertical load-bearing capacity of a single pile – EFFECTIVE STRESS analysis method

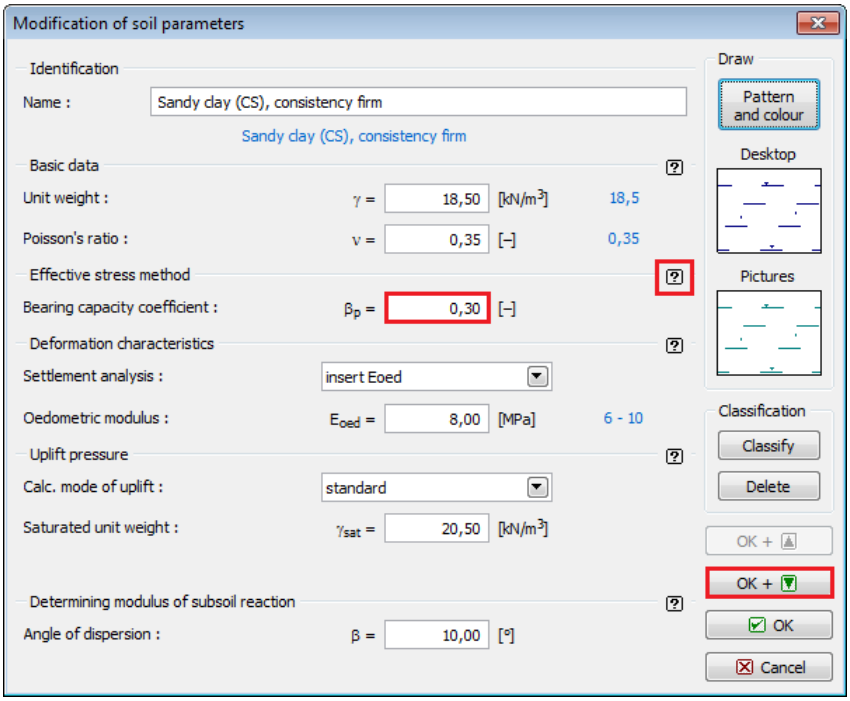
Now we will get back to the input data settings and will carry out the analysis of the vertical bearing capacity of a single pile for the other analysis methods (Effective stress and CSN 73 1002).

In the "Settings" frame we will click on the "Edit" button. In the "Piles" tab sheet, at the drained conditions calculation, we will select the "Effective stress" option. The other parameters will remain unchanged.



Dialogue window „Edit current settings“

Then we will proceed to the “Soils” frame, where we in addition define for this analysis method the coefficient of pile bearing capacity β_p $[-]$, which affects the magnitude of skin friction R_s $[kN]$. This parameter is determined according to the soil internal friction angle φ_{ef} $[°]$ and the soil type (for more details visit Help – F1).



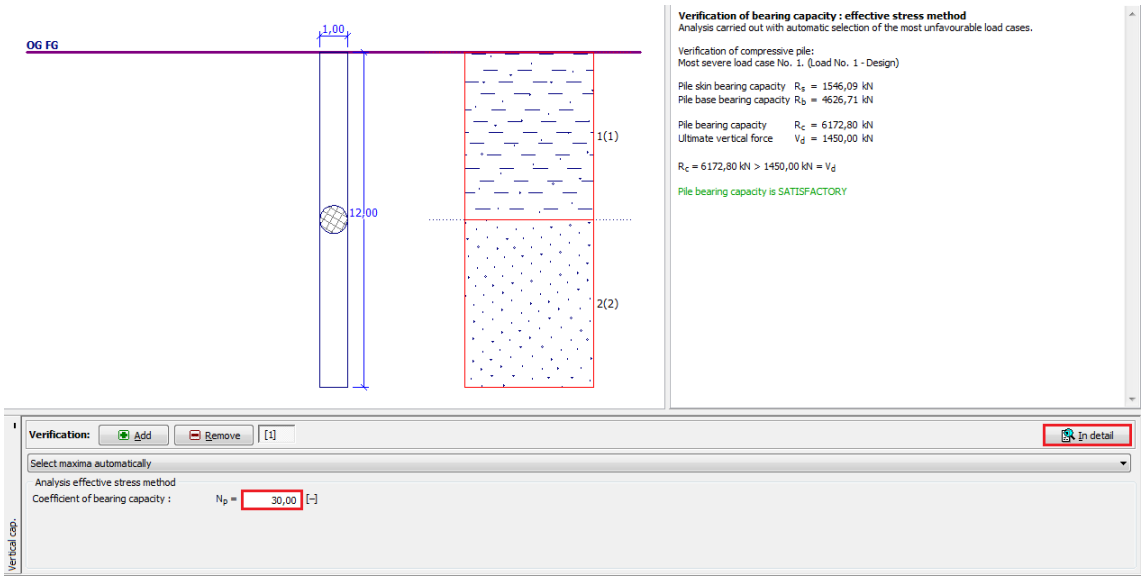
Dialogue window „Modification of soil parameters“

The other frames remain unchanged. Now we will get back to the "Vertical capacity" frame. For the **Effective Stress** method we must first specify the value of the coefficient of bearing capacity N_p $[-]$, which significantly affects the pile base bearing capacity R_b $[kN]$. This parameter is determined according to the size of the soil internal friction angle φ_{ef} $[°]$ and the soil type (for more details visit Help – F1).

The significant influence of this parameter on the result is demonstrated by the following table:

- for $N_p = 10$ (pile base in *clayey* soil): $R_b = 1542.44\ kN$,
- for $N_p = 30$ (pile base in *sandy* soil): $R_b = 4626.71\ kN$,
- for $N_p = 60$ (pile base in *gravelly* soil): $R_b = 9253.42\ kN$.

For our particular problem specification we consider the coefficient of bearing capacity $N_p = 30$ (the pile base in *sandy* soil). The guidance values of N_p can be found in Help – for more details visit F1.

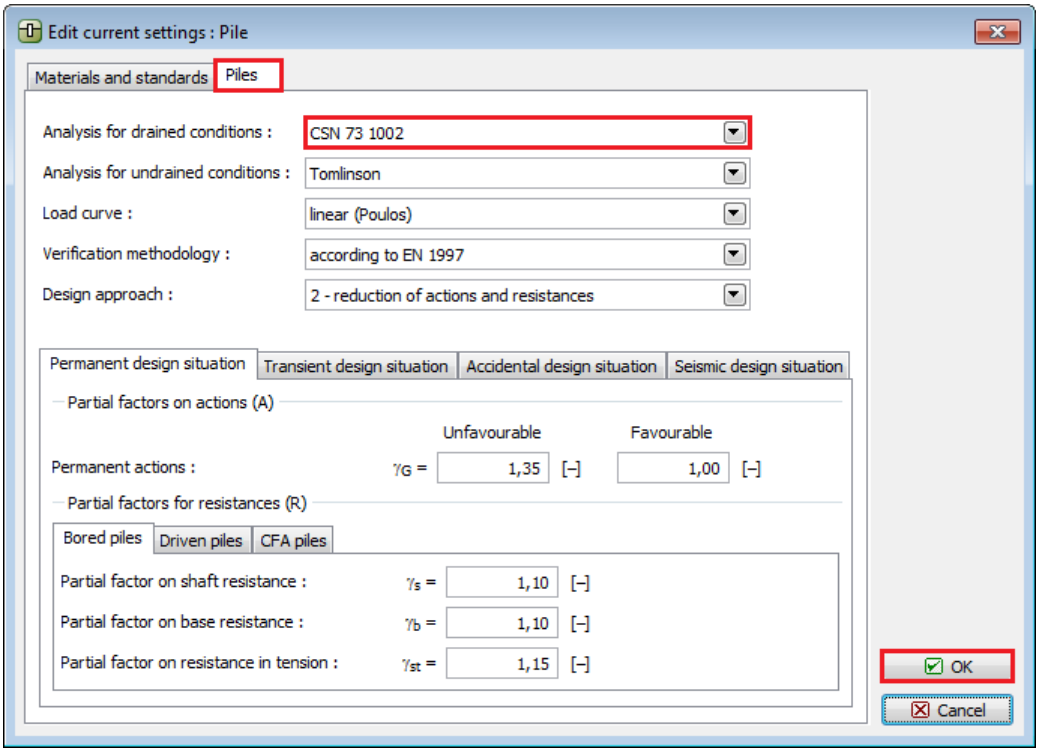


"Vertical capacity frame – assessment according to the Effective Stress method"

- **EFFECTIVE STRESS**: $R_c = 6172.8\ kN > V_d = 1450.0\ kN$ … SATISFACORY.

Analysis of vertical load-bearing capacity of a single pile – CSN 73 1002 analysis method

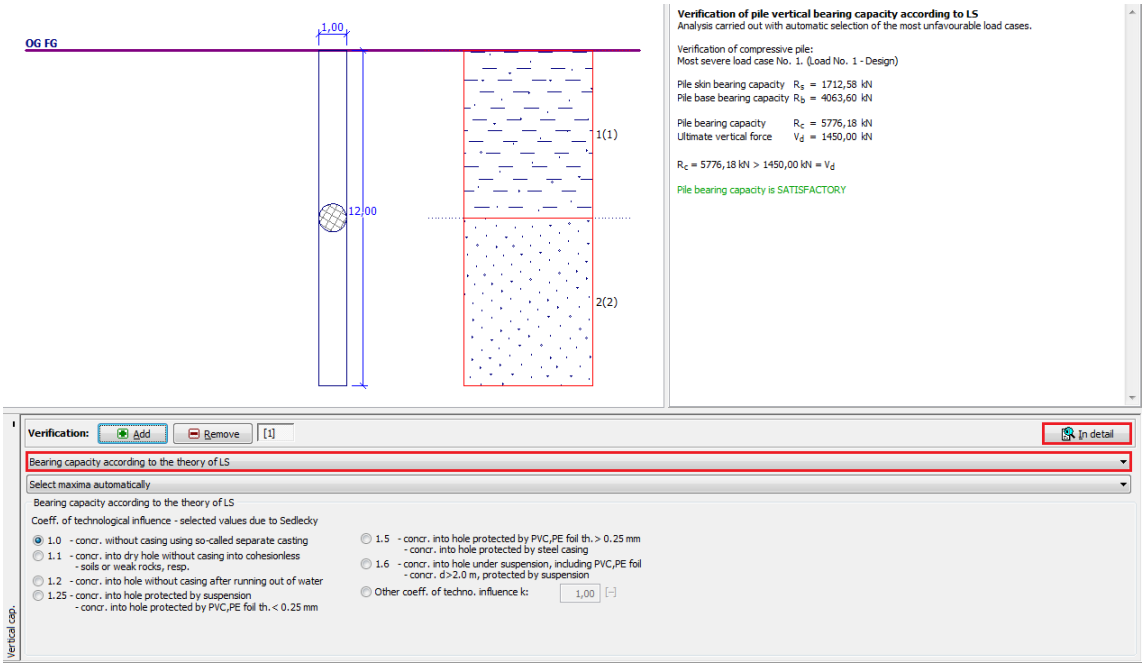
Now we will get back to the frame in the "Settings" frame, where we will change the analysis method for drained conditions in the dialogue window "Edit current settings" to „*CSN 73 1002*". All of the other input parameters will remain unchanged.



Dialogue window „Edit current settings"

Note: The analysis procedure is presented in the publication „Pile foundations – Comments on CSN 73 1002" (Chapter 15: Designing, part B – General solution according to group 1 of the limit states theory, page 15). All program procedures are based on the relationships contained in this text, with the exception of calculation coefficients, which depend on the assessment methodology adopted (for more details visit Help - F1).

Subsequently we will re-assess the pile in the "Vertical capacity" frame. We will leave the coefficient of technological influence equal to 1.0 (the analysis of vertical load-bearing capacity of a pile without the reduction due to the installation technology).



„Vertical capacity – assessment according to CSN 73 1002" frame

– **CSN 73 1002**: $R_c = 5776.18\ kN > V_d = 1450.0\ kN$ … SATISFACTORY.

Vertical load-bearing capacity of a single pile analysis results:

The values of the total vertical bearing capacity R_c of a pile differ depending on the analysis methods used and the input parameters assumed by these methods:

– *NAVFAC DM 7.2*: adhesion factor $\alpha\ [–]$,
pile skin friction angle $\delta\ [°]$,
coefficient of lateral soil stress $K\ [–]$,
critical depth analysis coefficient $k_{dc}\ [–]$,
coefficient of bearing capacity $N_q\ [–]$.

– *EFFECTIVE STRESS*: coefficient of pile bearing capacity $\beta_p\ [–]$,
coefficient of bearing capacity $N_p\ [–]$.

– *CSN 73 1002*: soil cohesion $c_{ef}\ [kPa]$,
soil internal friction angle $\varphi_{ef}\ [°]$.

The results of the analysis of the vertical bearing capacity of a single pile in drained conditions relative to the analysis method used are presented in the following table:

EN 1997-1, DA2 (drained conditions) Analysis method	Pile skin bearing capacity $R_s\ [kN]$	Pile base bearing capacity $R_b\ [kN]$	Vertical bearing capacity $R_c\ [kN]$
NAVFAC DM 7.2	676.82	1542.24	2219.06
EFECTIVE STRESS	1546.09	4626.71	6172.80
CSN 73 1002	1712.58	4063.60	5776.18

Summary of results – Vertical bearing capacity of pile in drained conditions

The total vertical bearing capacity of a centrally loaded single pile R_c is higher than the value of the design load V_d acting on it. The fundamental reliability condition for the ultimate limit state is met; the pile design is therefore satisfactory.

Conclusion:

It follows from the analysis results that the total vertical bearing capacity of a pile is different. This fact is caused both by the different input parameters and by the chosen analysis method.

The assessment of piles depends first of all on the chosen analysis method and input parameters describing the soil. Designers should always use such calculation procedures for which they have required soil parameters available resulting from the results of engineering geological surveys and which reflect local practices.

It is certainly improper to assess a pile using all analysis methods contained in the program and choose the best or the worst results.

For the Czech and Slovak Republics the GEO 5 software authors recommend calculating the vertical load-bearing capacity of a single pile using the following two methods:

a) An analysis taking into consideration the value of the allowable settlement $s_{\lim} = 25\ mm$ (the procedure according to ***Masopust***, which is based on the solution to regression curves equations).

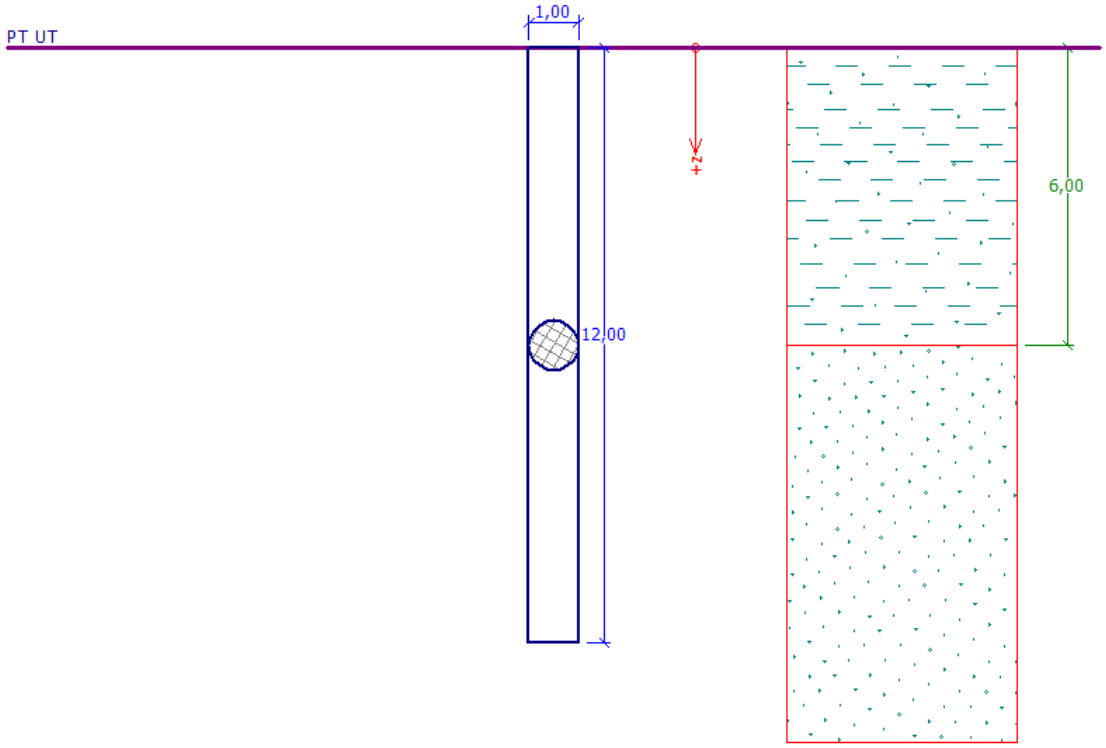
b) An analysis according to ***CSN 73 1002***. The pile analysis procedure remains identical with that contained in CSN, but the loading and calculation coefficients reducing the soil parameters or the pile resistance are specified according to EN 1997-1. This analysis therefore fully complies with EN 1997-1.

Chapter 15. Analysis of a single pile settlement

The objective of this chapter is to explain the application of the GEO 5 – PILES program for the analysis of the settlement of a single pile to a specified practical problem.

Problem specification:

The general problem specification is described in chapter *13. Pile foundations – Introduction.* All analyses of the single pile settlement shall be carried out as a follow-up to the previous problem presented in chapter *14. Analysis of vertical load-bearing capacity of a single pile*.



Problem specification chart – single pile

Solution:

We will apply the GEO 5 – PILES program to the analysis of this problem. In the text below we will describe the solution to this example step by step.

In this analysis we will calculate the settlement of a single pile using the following methods:

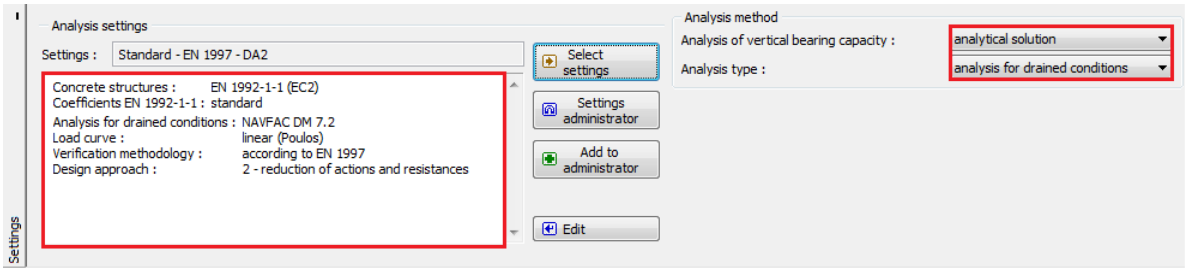
- *linear settlement theory* (according to Prof. **Poulos**),
- *nonlinear settlement theory* (according to **Masopust**).

Linear loading curve (solution according to Poulos) is determined from the results of the calculation of the vertical bearing capacity of the pile. The fundamental input into the calculation comprises **the pile skin bearing capacity and pile base bearing capacity values** – R_s and R_b. These values are obtained from the previous analysis of the vertical bearing capacity of a single pile in dependence on the method applied (NAVFAC DM 7.2, Effective Stress, CSN 73 1002 or Tomlinson).

Nonlinear loading curve (solution according to Masopust) is based on the specification using the so-called **regression coefficients.** The result is therefore independent of the load-bearing capacity analysis methods and can be therefore used even for the determination of the vertical bearing capacity of a single pile, where the capacity corresponds to the allowable settlement (usually 25 mm).

Specification procedure: The linear settlement theory (POULOS)

We will leave the analysis settings unchanged as „Standard – EN 1997 – DA2“ according to the previous problem, the analysis of bearing capacity according to NAVFAC DM 7.2. The linear loading curve (Poulos) has already been specified for these analysis settings.



„Analysis settings“ frame

Note: The analysis of the limit loading curve is based on the theory of elasticity. Ground is described by the modulus of deformation E_{def} and Poisson's ratio ν.

This method makes the determination of the limit loading curve possible for the following piles:

- **end-bearing piles:** suitable for common soil types, e.g. medium dense and dense cohesionless soils (sands, gravels), stiff and hard clays, hard rock and semi-rock sub-grade – in this case the pile base transfers part of the load to the soil.

– **floating piles:** suitable for the use in soft clays, floating sands and fine-grained cohesive soils (loess) – in this case zero pile base bearing capacity R_b is assumed.

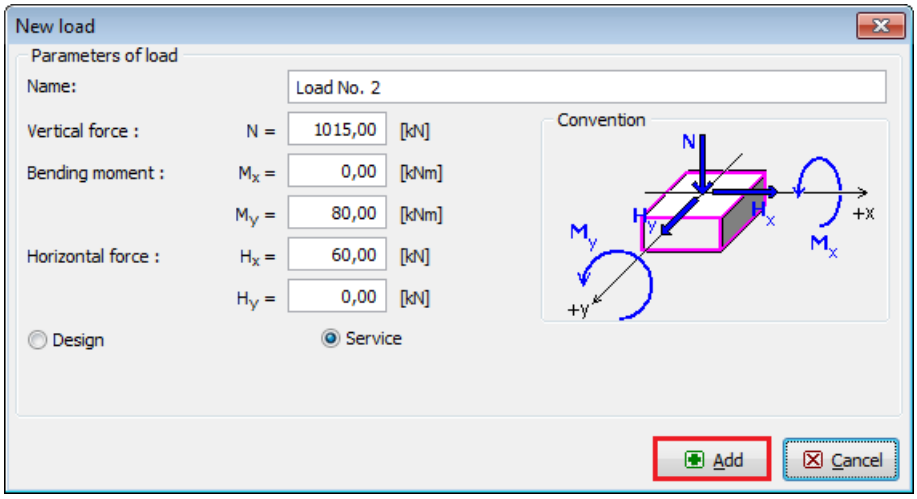
In this case the pile is installed in sands, therefore we will consider it as an end-bearing pile. The basic calculation condition is that the specific skin friction R_{sy} is determined for the moment when the pile skin bearing capacity no more increases and other loading is transferred only by the pile base (for more details visit Help – F1).

In the next step we will define the deformational properties of soils required for the analysis of settlement, i.e. oedometric modulus E_{oed}, or deformation modulus E_{def} and Poisson's ratio ν.

Soil (Soil classification)	Unit weight $\gamma\ [kN/m^3]$	Angle of internal friction $\varphi_{ef}\ [°]$	Cohesion of soil $c_{ef}\ [kPa]$	Poisson´s ratio $\nu\ [–]$	Oedometric modulus $E_{oed} = [MPa]$
CS – Sandy clay, firm consistency	18.5	24.5	14.0	0.35	8.0
S-F – Sand with trace of fines, medium dense soil	17.5	29.5	0.0	0.30	21.0

Soil parameters table – Settlement of single pile

For the purpose of analysing the settlement of a single pile we will define the service (working) load.

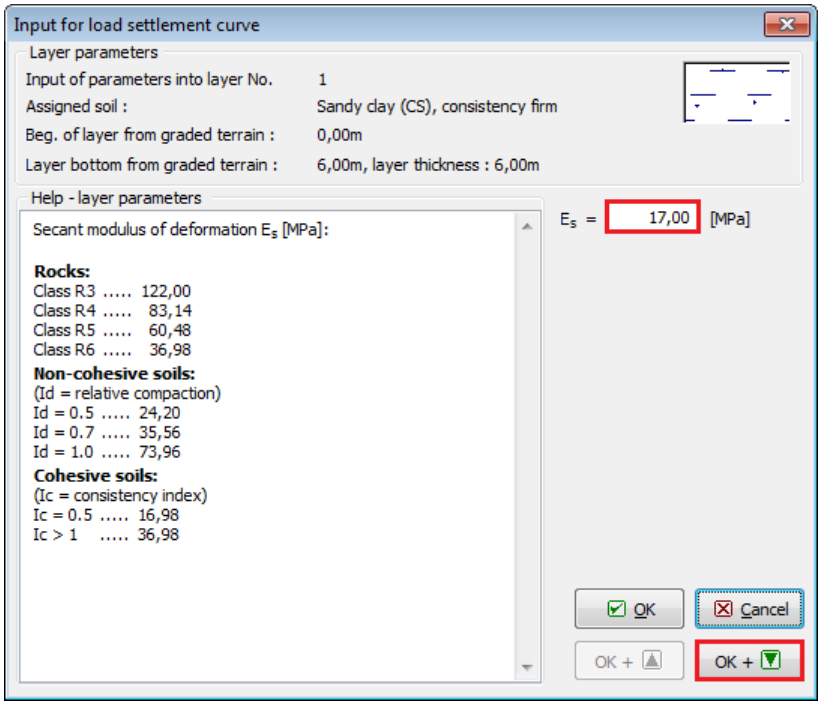


Dialogue window „New load"

We will leave the other frames out because they remain unchanged. Then we will go over to the settlement analysis in the "Settlement" frame.

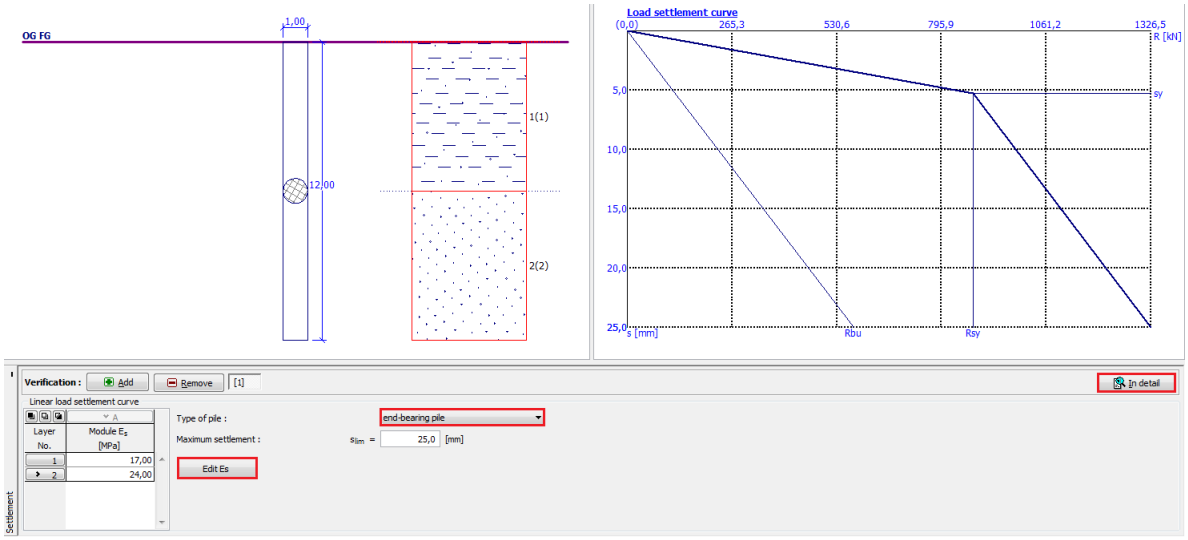
We will specify the secant modulus of deformation $E_s\ [MPa]$ for individual soil types using the „edit E_s" button.

For the 1st layer of *cohesive soil* (class CS, $I_c = 0.5$) we will set the recommended value of the secant modulus of deformation $E_s \cong 17.0\ MPa$. For the 2nd layer of *cohesionless soil* (class S-F, $I_d = 0.5$) we will assume the secant modulus of deformation value $E_s \cong 24.0\ MPa$ according to the table.



Dialogue window „ Input for load settlement curve – secant modulus of deformation E_s "

Note: The secant modulus of deformation E_s depends on the pile diameter and the thickness of individual soil layers. The values of this modulus should be determined on the basis of in-situ tests. Its value for cohesionless and cohesive soils further depends on the relative density index I_d and the consistency index I_c, respectively.



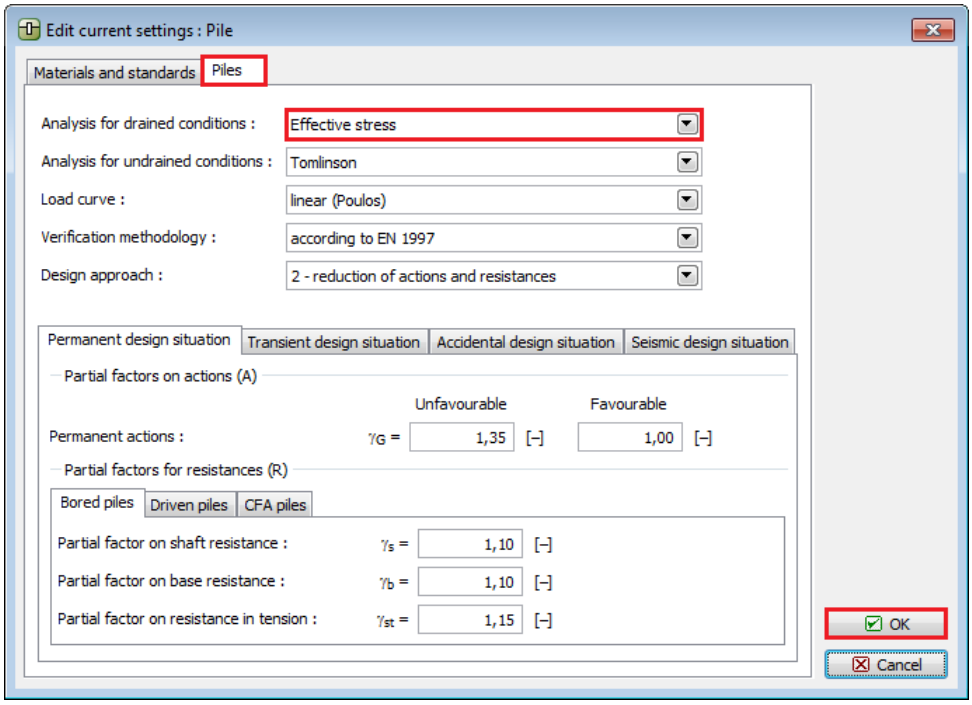
„Settlement" frame – Linear loading curve (solution according to Poulos)

Further we will set the limit settlement, which is the maximum settlement value for which the loading curve is calculated. We will click on "In detail" button and will present subtract the settlement value calculated for the maximum service load.

For the vertical bearing capacity analysis using the ***NAVFAC DM 7.2*** the resultant settlement of the single pile $s = 11.3\ mm$.

Single pile settlement analysis: Linear settlement theory (POULOS), the other methods

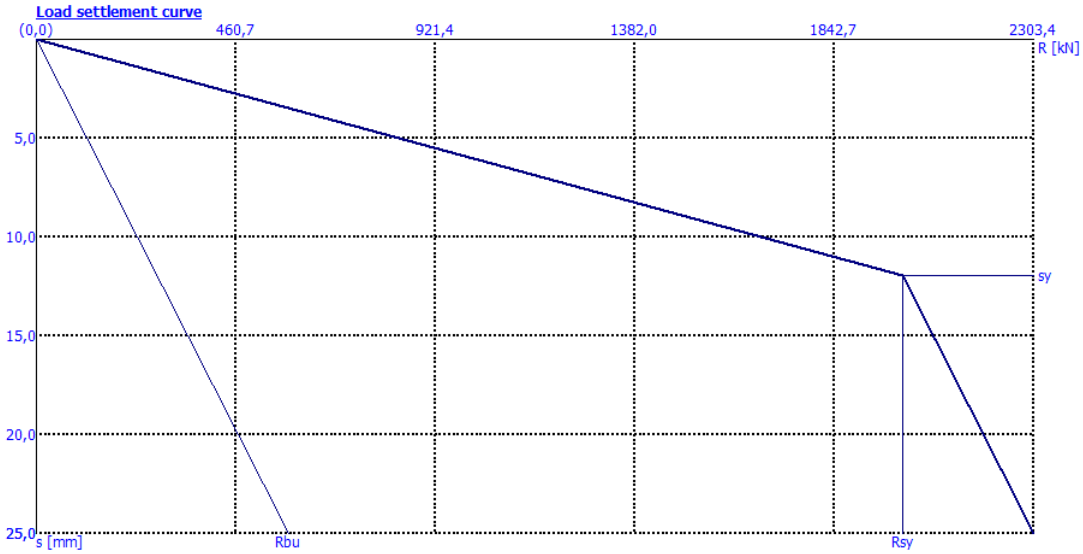
Now we will get back to the input data settings. In the "Settings" frame we will click on the "Edit" button. In the "Piles" tab sheet for the analysis for drained conditions we will first select the option "Effective Stress", and then the option "CSN 73 1002" for the next analysis. The other input parameters will remain unchanged.



Dialogue window „Edit current settings“

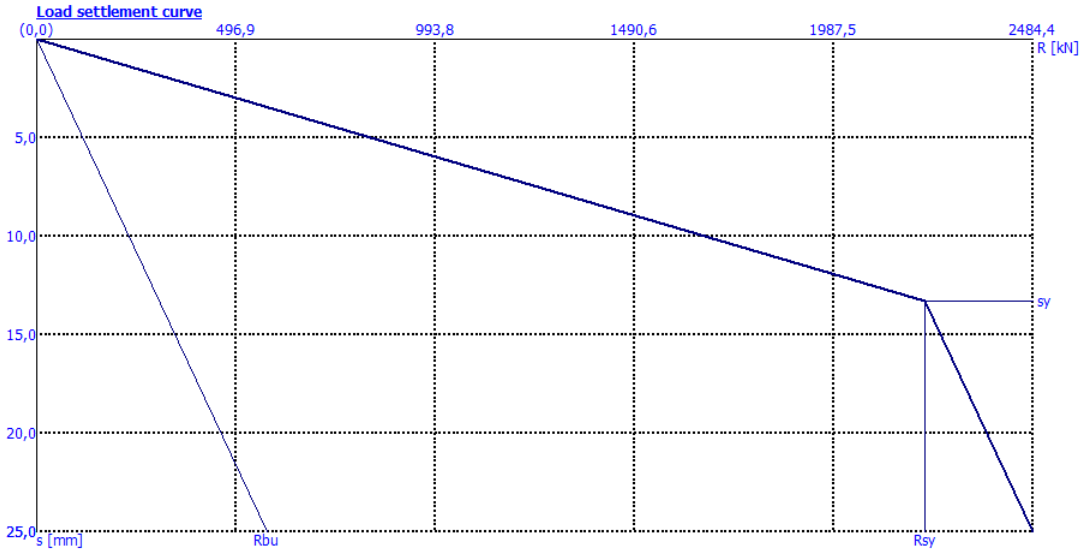
Subsequently we will get back to the “Settlement” frame, where we will see the results. The magnitude of the limit settlement $s_{\lim}$, the pile type and the secant modulus of deformation E_s remain identical with those used in the previous case.

For the vertical bearing capacity of a single pile determined using the ***EFFECTIVE STRESSES*** method, the resultant settlement $s = 6.1\ mm$.



„Settlement“ frame – Linear loading curve (according to Poulos) for the Effective Stresses method

For the vertical bearing capacity of a single pile which is determined for the ***CSN 73 1002*** method, the analysis of the pile settlement $s = 6.1\ mm$.



„Settlement" frame – Linear loading curve (according to Poulos) for the CSN 73 1002 method

Results of the single pile settlement analysis according to the linear theory (***Poulos***) in dependence on the vertical bearing capacity analysis method used are presented in the following table:

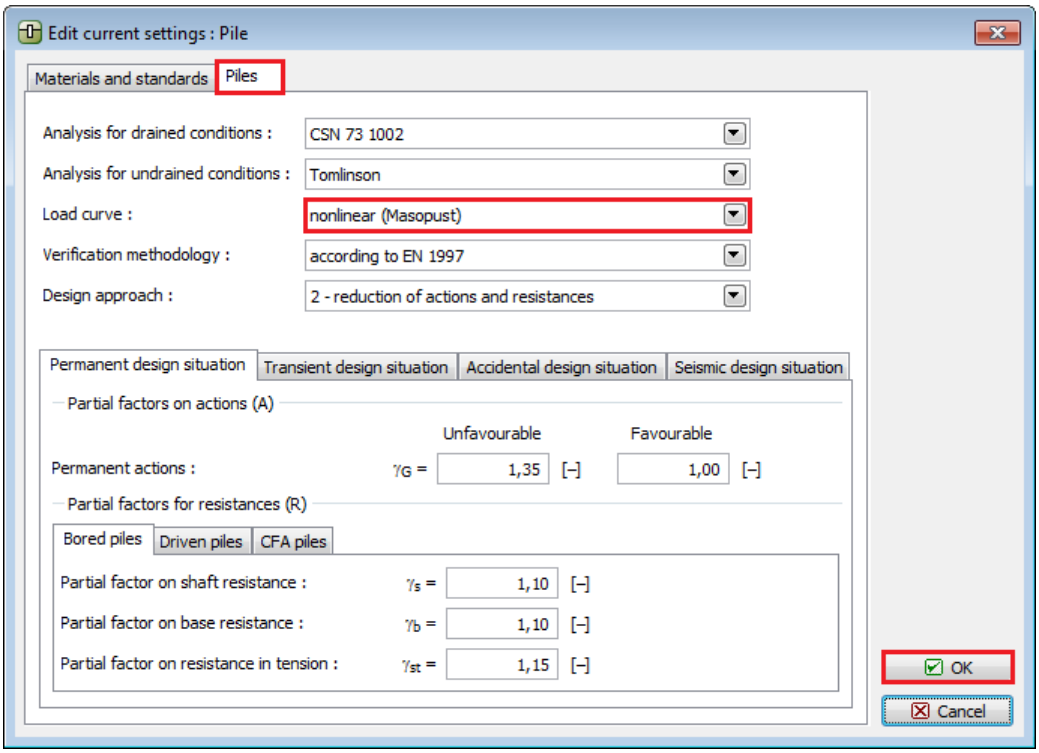
Linear loading curve Analysis method	Load at the onset of mobilization of skin friction $R_{yu}\ [kN]$	Total resistance $R_c\ [kN]$ for $s_{\lim} = 25{,}0\ mm$	Settlement of single pile $s\ [mm]$
NAVFAC DM 7.2	875.73	1326.49	11.3
EFECTIVE STRESS	2000.47	2303.40	6.1
CSN 73 1002	2215.89	2484.40	6.1

Summary of results – Settlement of single pile according to Poulos

Analysis of single pile settlement: Nonlinear settlement theory (MASOPUST)

This solution is independent of previous analyses of the vertical bearing capacity of a pile. The method is based on the solution to regression curves equations according to the results of static pile loading tests. This solution method is used first of all in the Czech and Slovak Republics. It provides reliable and conservative results for local engineering geological conditions.

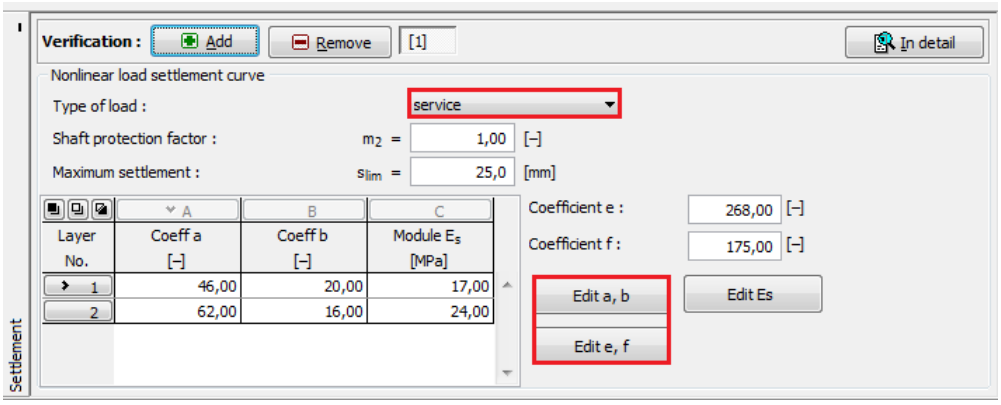
We will click on the "Edit" button in the "Settings" frame. In the "Piles" tab sheet for the loading curve we will choose the "nonlinear" option (Masopust)".



Dialogue window "Edit current settings"

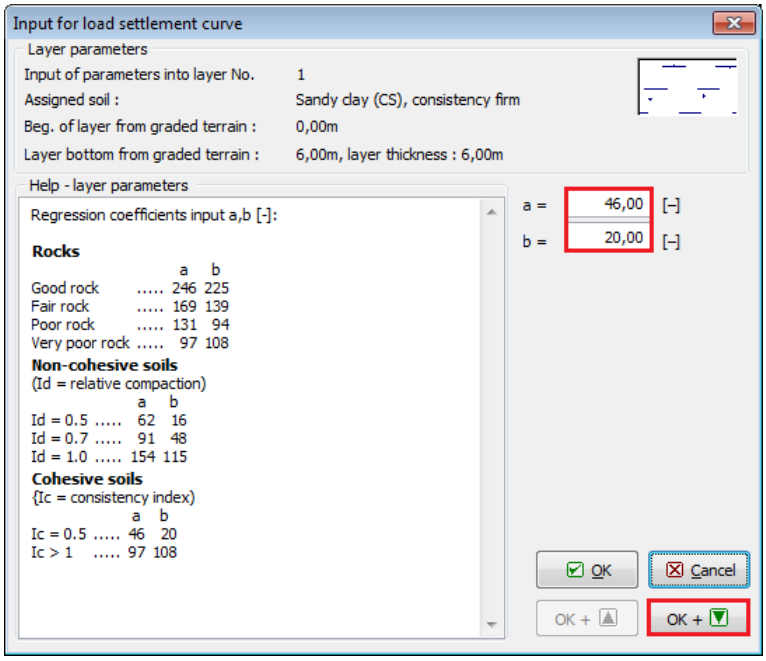
The other data remains unchanged. Then we will go over to the "Settlement" frame.

We consider the *service load* for the nonlinear limit loading curve because this is the case of the analysis according to the limit state of serviceability. We will leave the shaft protection factor value at $m_2 = 1.0$, therefore we will not reduce the resultant value of the vertical bearing capacity of the pile with respect to the installation technology. We will leave the values of the allowable (maximum) settlement s_{lim} and secant modulus of deformation E_s identical with those used in previous analyses.



„Settlement" frame – solution according to the nonlinear settlement theory (Masopust)

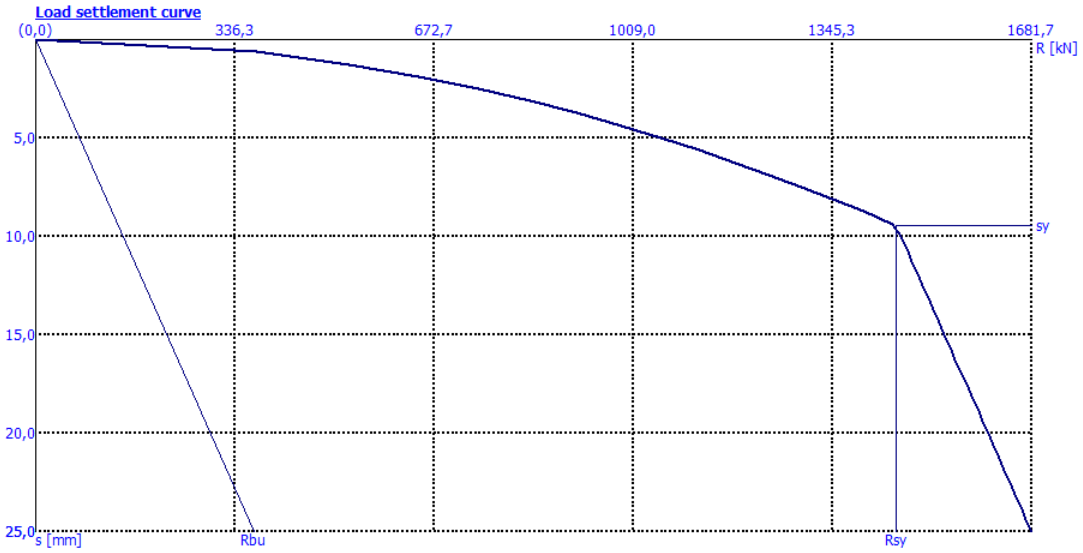
Further we will set the values of regression coefficients using the "*Edit a, b*" and "*Edit e, f*" buttons. When editing is being carried out, values of regression coefficients recommended for various types of soils and rocks are displayed in the dialogue window.



Dialogue window „Input for load settlement curve – regression coefficients a, b (e, f)"

Note: The specific skin friction depends on regression coefficients „a, b". The stress on the pile base (at fully mobilised skin friction) depends on regression coefficients "e, f". The values of these regression coefficients were derived from regression curves equations determined on the basis of a statistical analysis of results of about 350 static pile loading tests in the Czech and Slovak Republics (for more details visit Help – F1). For cohesionless soils and cohesive soils, these values depend on the relative density index I_d and the consistence index I_c, respectively (for more details visit Help – F1).

The pile settlement for the specific service load $s = 4.6\ mm$.



„Settlement" frame – Nonlinear loading curve (according to Masopust)

Note: This method is used even for the pile load-bearing capacity analysis, where the program calculates on its own the pile bearing capacity for the limit settlement (usually 25 mm).

Total load-bearing capacity for $s_{\lim}$: $R_c = 1681.67\ kN > V_d = 1015.0\ kN$ … Satisfactory.

Conclusion:

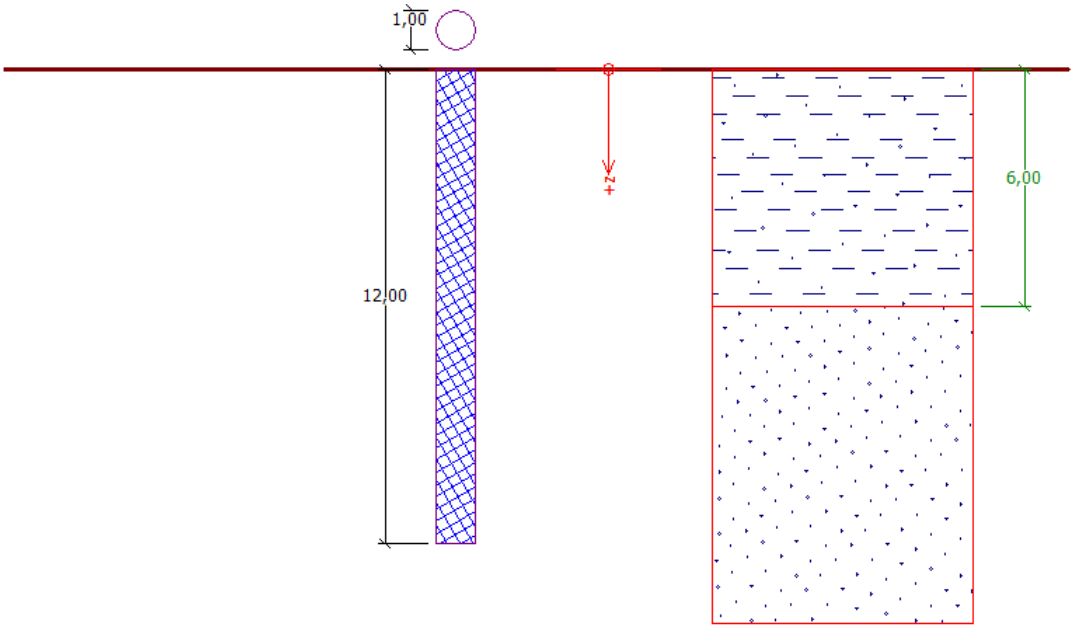
The program calculated the pile settlement for the specified service load to be within the range of 4.6 to 11.2 mm (depending on the method used). This settlement is smaller than the maximum allowable settlement – the pile is satisfactory from the 2nd limit state point of view.

Chapter 16. Analysis of vertical load-bearing capacity and settlement of piles investigated on the basis of CPT tests

The objective of this chapter is to explain the use of the GEO 5 – CPT PILE program.

Problem specification:

The general problem specification is described in the previous chapter (*13. Pile foundations – Introduction*). Analyse the load-bearing capacity and settlement of a single pile, or a pile group according to the EN 1997-2.

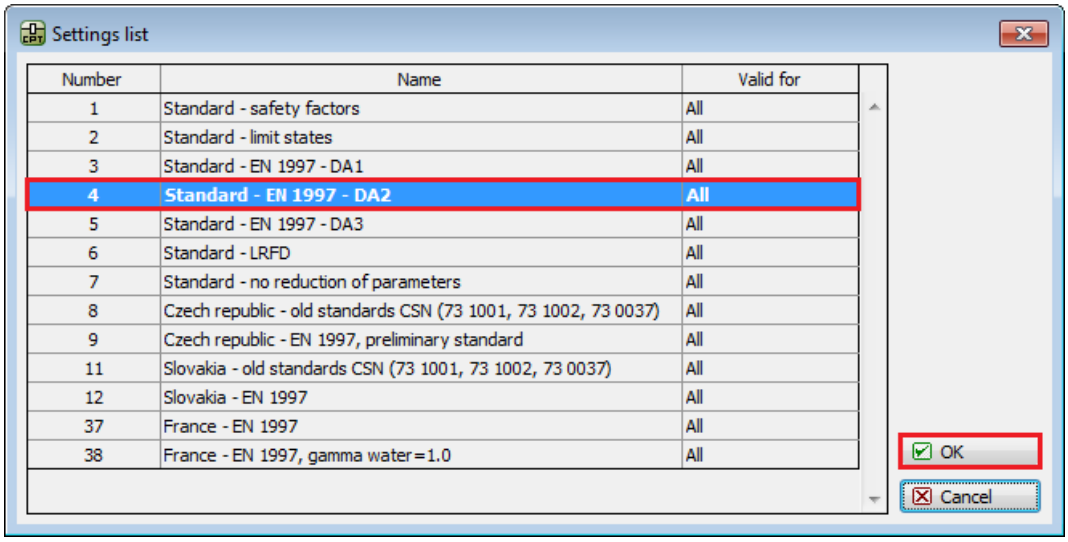


Problem specification chart – single pile investigated according to CPT tests

Solution:

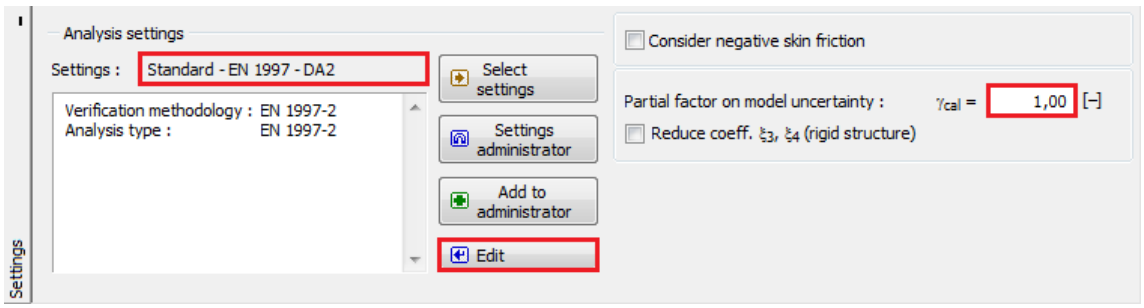
We will apply the GEO 5 – CPT PILE program to the analysis of this problem. In the text below we will describe the solution to this example step by step.

We will click on the "Select setting" button (at the bottom left of the screen) in the "Settings list" frame and then we will choose the "Standard – EN 1997" analysis settings. The design approach is not important, the analysis is carried out in accordance with the *EN 1997-2* standard: *Geotechnical Design – Part 2: Ground investigation and testing*.



Dialogue window „Settings list“

In the first analysis we will assess a single pile, we therefore will not specify the reduction of correlation coefficients ξ_3, ξ_4. We will not take the influence of the negative skin friction into consideration. In this frame it is also possible to specify the *partial factor of model uncertainty*, which is used for reducing the total calculated bearing capacity of the pile – we will leave the standard value of 1.0.

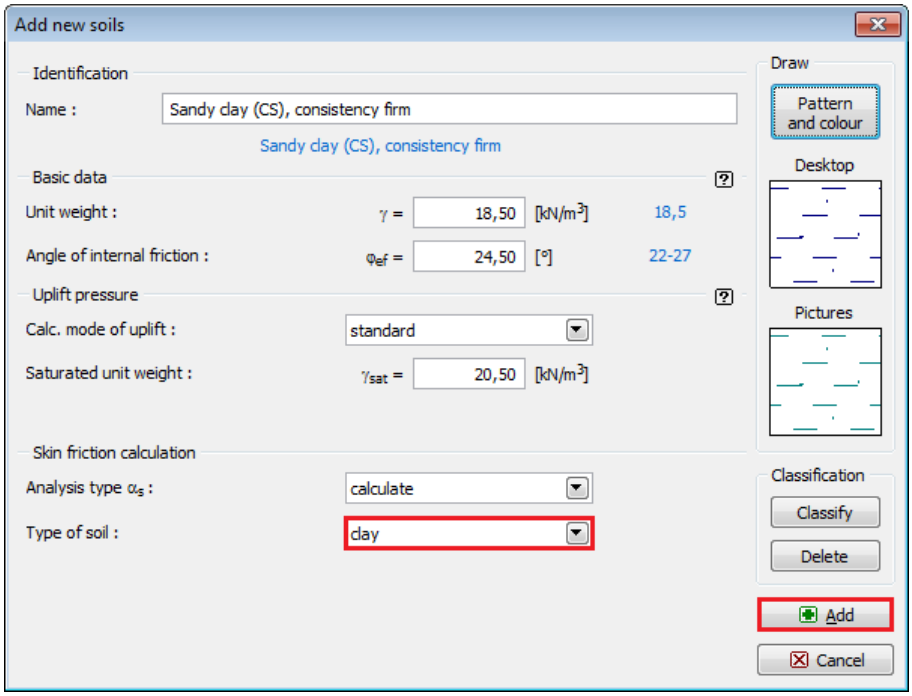


„Settings“ frame

Note: Correlation coefficients ξ_3, ξ_4, thus even the total bearing capacity of the pile, depend on the number of completed CPT tests. When we have got more completed CPT tests available, the magnitude of the correlation coefficients is smaller. For 1 completed static penetration test the values are $\xi_3, \xi_4 = 1.4$ according to ***Table A.10 - Correlation coefficients for deriving characteristic values of pile capacities from ground tests*** *presented in EN 1997-1 (Part A.3.3.3).*

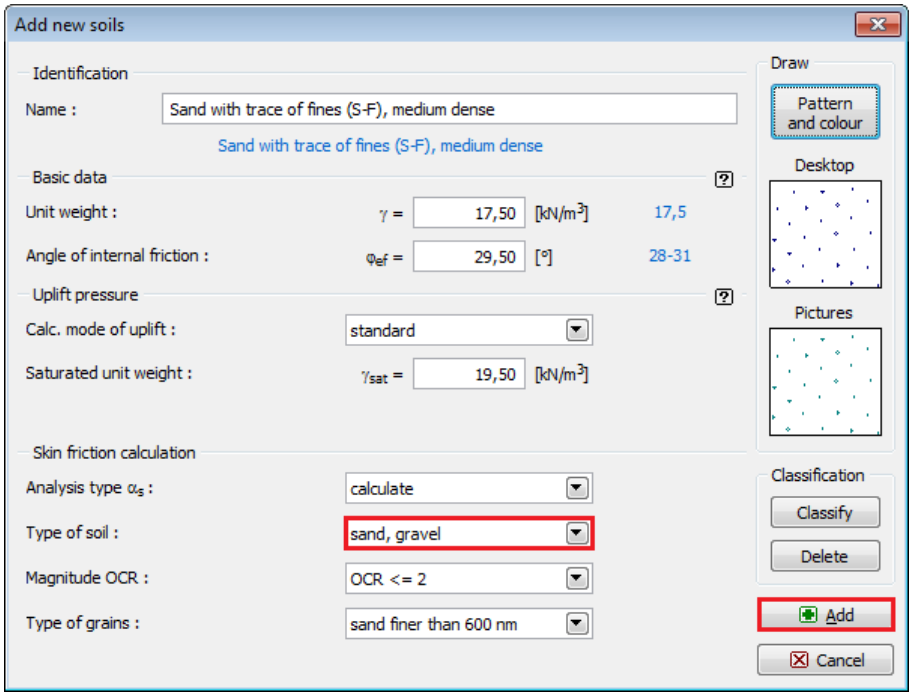
In the next step we will define the parameters of soil types to be used in the analysis and will assign them to the profile. For the assessment according **EN 1997-2** we must first define the *soil type*, whether the soil layer is clayey or sandy or gravelly. The soil type determines the magnitude of coefficients for the calculation of skin friction and the pile base bearing capacity.

Further we will set the internal friction angle size and the volume weight. We will leave the calculated skin friction reducing coefficient α_s with the possibility of additional calculation – the program allows users to enter these values in special cases by hand, but using coefficients according to respective standards is a common procedure (for more details visit Help – F1).



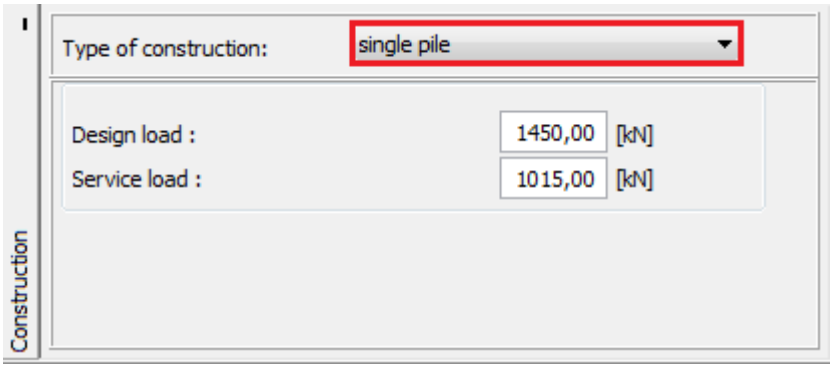
Dialogue window „Add new soils" – Clayey soil (class F4)

In the cases of sandy and gravelly soils we must in addition enter the size of grains and the overconsolidation ratio (OCR). This parameter reduces the value of maximum stress on pile base $p_{\max,\ pata}\ [MPa]$. In our particular case we consider this value as $OCR \leq 2.0$ and the grain size as "sand finer than 600 *nm*". (For more details visit Help – F1).



Dialogue window „Add new soils" – Sand with trace of fines (class S3)

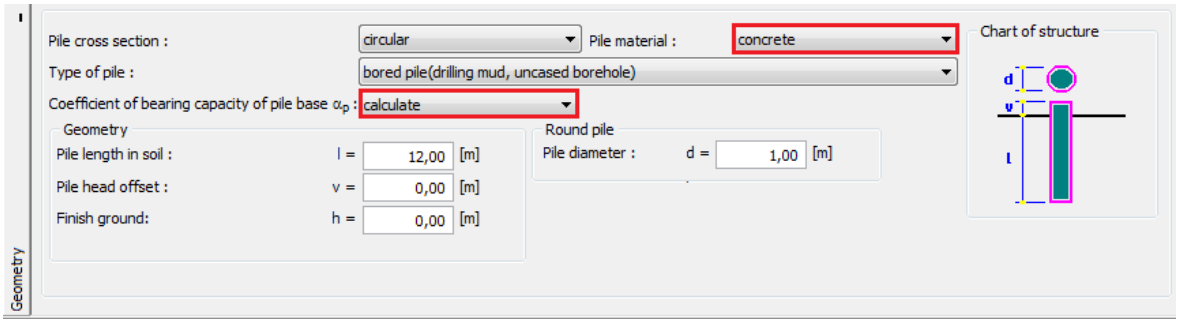
In the "Type of construction" frame we will choose the "single pile" option. Then we will enter the maximum magnitude of vertical load acting on the pile. The design load and service load are used for the pile bearing capacity analysis and the pile settlement analysis, respectively.



„Type of construction" frame

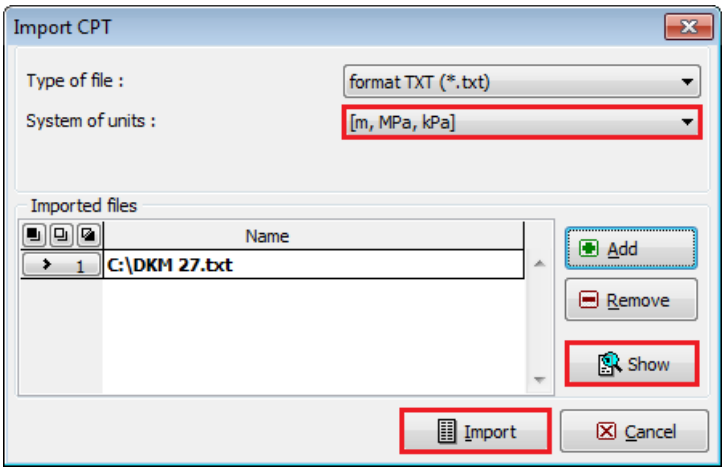
In the "Geometry" frame we will enter the pile material and cross-section, specify basic dimensions, i.e. the pile diameter and length in soil. Subsequently we will define the pile execution technology. In this particular case we have bored piles, with the borehole uncased or stabilised with drilling mud.

We will maintain the calculation of the coefficient of pile base resistance α_p, with the possibility of additional calculation (similarly to coefficient α_s).

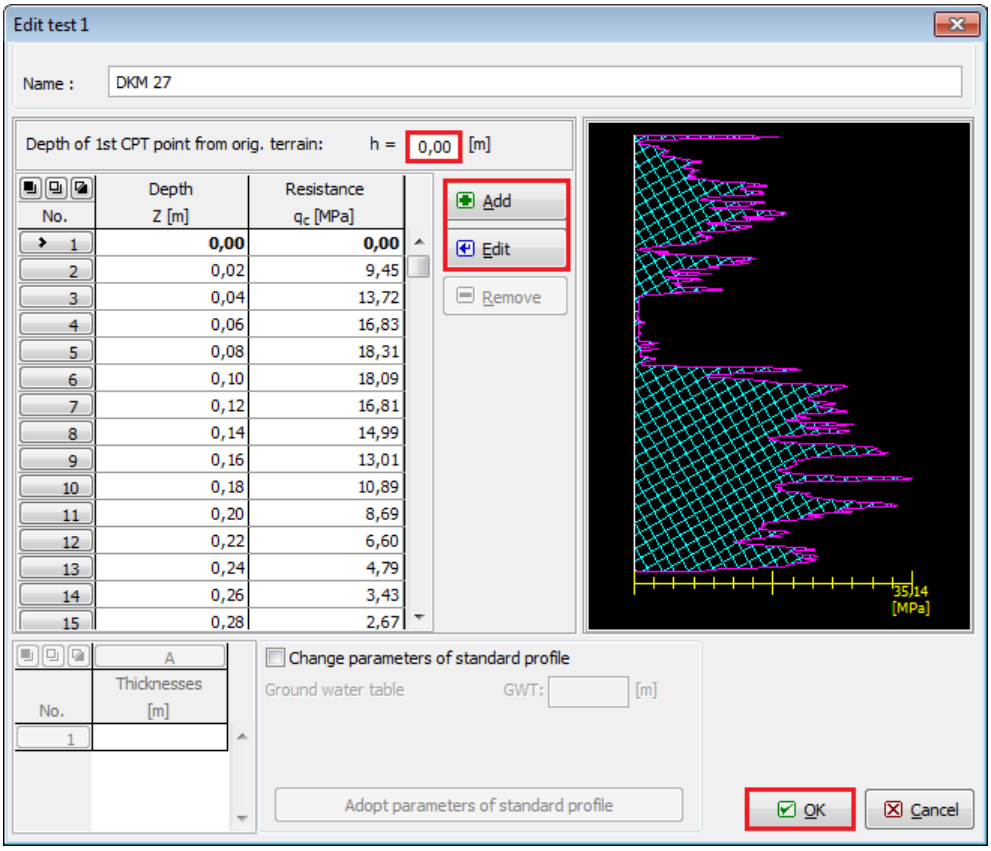


„Geometry“ frame

In the “Import CPT” frame we will import completed tests into the program. In this particular case we will import the CPT tests into the program in the *.TXT format (using the „Import“ button), for which we will choose the metric unit system $[m, MPa, kPa]$. Clicking on the “Show” button will open the preview of the given file from which we will import the respective data. Then we will confirm everything by the “Import” button.

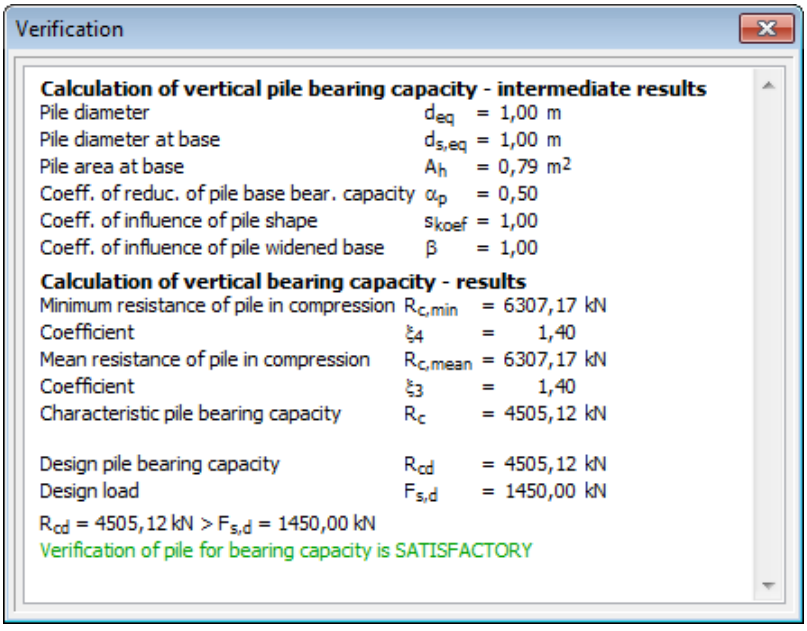


Dialog window „Import CPT“



Dialogue window „Edit test“

Now we will go over to the verification of the single pile using the “Bearing capacity” frame, in which we will check the calculation results. By clicking on the “In Detail” button we will in addition show intermediate results for the vertical pile bearing capacity analysis.

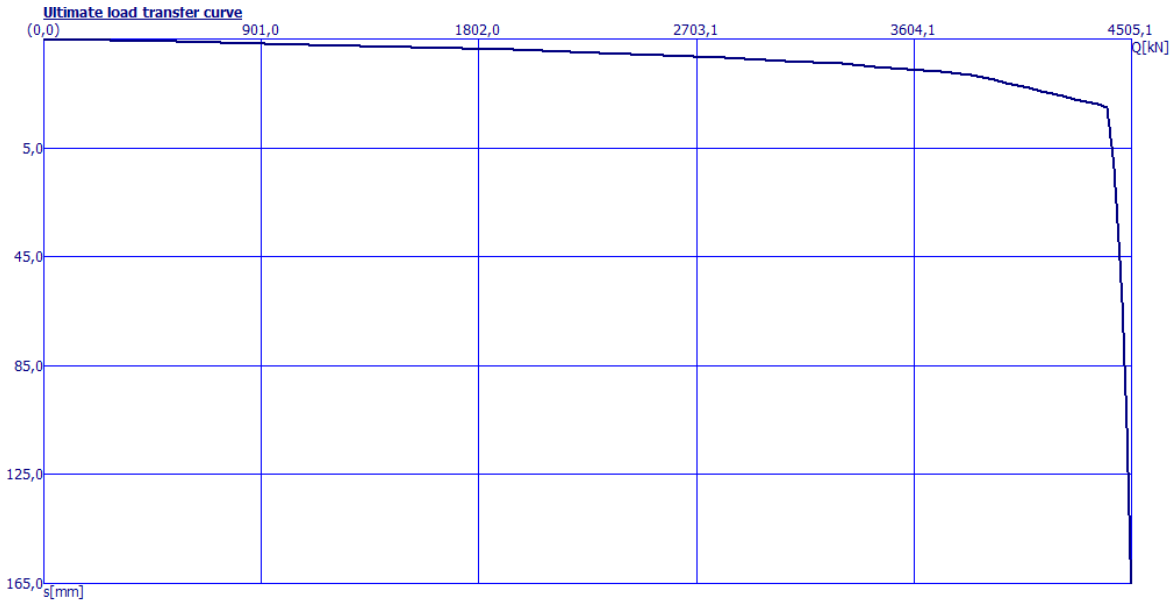


Dialogue window „Verification (detailed)“ – Vertical bearing capacity

The vertical bearing capacity of a pile $R_{c,d}$ consists of the summary of skin friction and pile base resistance (for more details visit Help – F1). To meet the reliability condition, its value must be higher than the magnitude of the acting design load $F_{s,d}$.

– **EN 1997-2**: $R_{c,d} = 4505.12\ kN > F_{s,d} = 1450.0\ kN$ … SATISFACTORY.

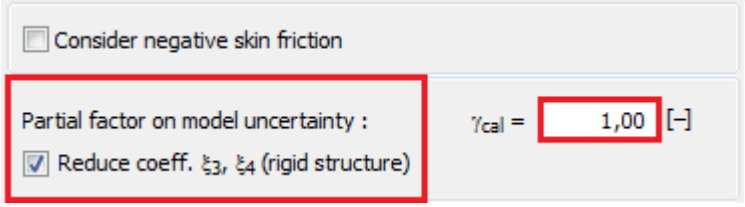
Subsequently we will go over to the "Settlement" frame, displaying the ultimate loading curve for the pile and the results of the total pile settlement $w_{1,d} = 2.2\ mm$ for service load $F_s = 1015\ kN$.



„Settlement" frame – Ultimate loading curve (working diagram) for a pile

Specification procedure and analysis: Pile group

Now we will carry out the assessment of a pile group with a rigid grid. In the "Settings" frame we will choose the option "Reduce coefficients ξ_3, ξ_4 (rigid structure)".



„Settings" frame

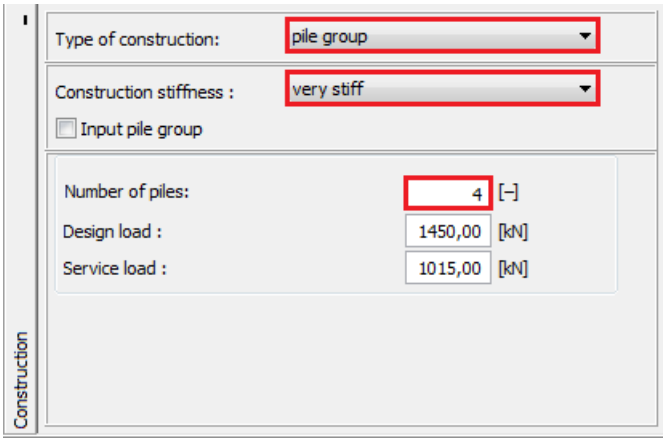
*Note: Characteristic values of bearing capacities $R_{b;k}$ and $R_{s;k}$ will be determined according to the following relationship, which is contained in EN 1997-1 (clause **7.6.2.3 Ultimate compressive resistance from ground test results**:*

$$R_{c;k} = \left(R_{b;k} + R_{s;k}\right) = \frac{R_{b;cal} + R_{s;cal}}{\xi} = \frac{R_{c;cal}}{\xi} = \min\left\{\frac{\left(R_{c;cal}\right)_{mean}}{\xi_3}; \frac{\left(R_{c;cal}\right)_{\min}}{\xi_4}\right\}$$

Correlation coefficients ξ_3, ξ_4 depend on the number of tests (testing profiles) n; they will be applied to:

- *average bearing capacity value $\left(R_{c;cal}\right)_{mean} = \left(R_{b;cal} + R_{s;cal}\right)_{mean}$,*
- *highest values of the calculated bearing capacity $\left(R_{c;cal}\right)_{\min} = \left(R_{b;cal} + R_{s;cal}\right)_{\min}$.*

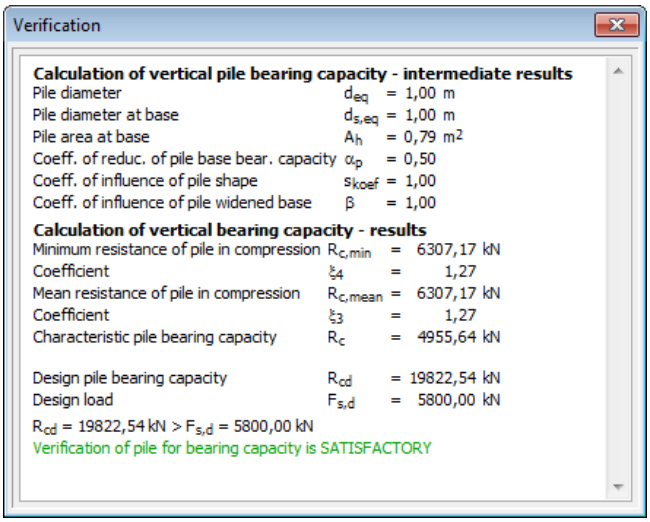
Then we will go over to the "Construction" frame, where we will define parameters required for the pile group analysis. We will consider the pile foundation (pile cap with piles) to be a **rigid structure**, where it is assumed that ***all piles settle equally***. Further we will set the number of piles $n = 4$.



„Construction" frame

The other frames remain unchanged.

Now we will get back to the "Bearing capacity" frame, where the assessment results are displayed.



Dialogue window „Verification (detailed)" – Vertical bearing capacity

– **EN 1997-2**: $R_{c,d} = 19\,822.54\ kN > F_{s,d} = 5\,800.0\ kN$ … SATISFACTORY.

Conclusion:

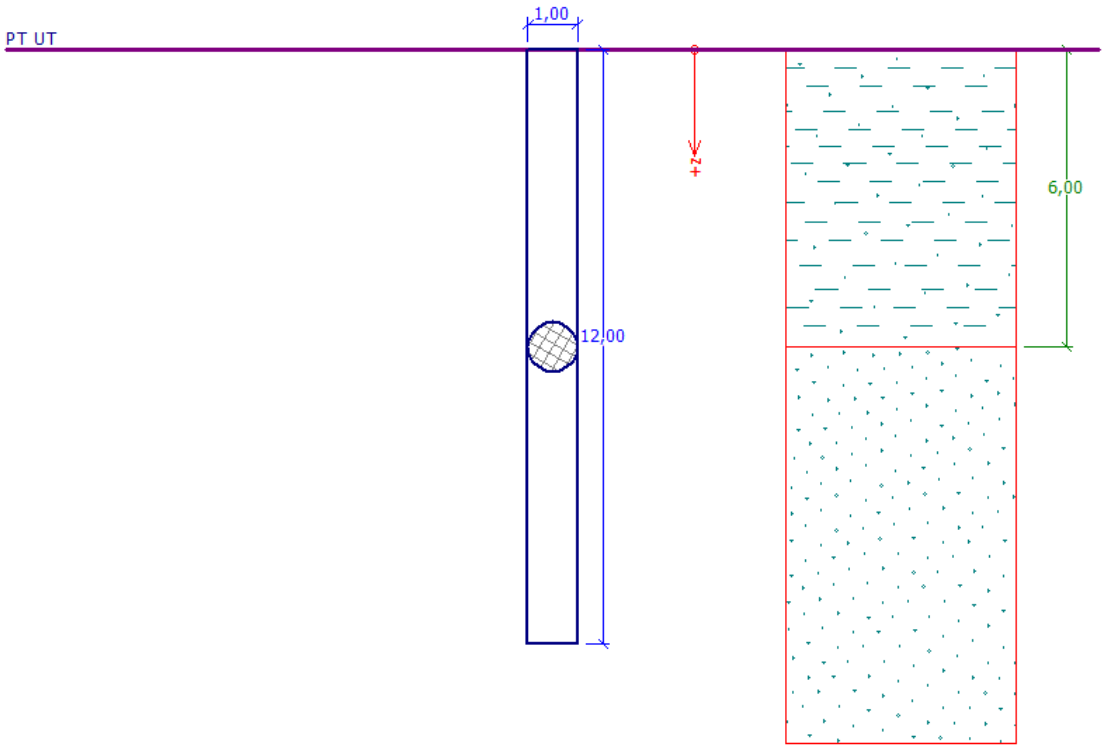
The vertical bearing capacity of the pile or the pile group being assessed is satisfactory. The main advantage of the CPT tests based analysis is its speed and unambiguousness. This procedure is precisely described in *EN 1997-2: Geotechnical Design – Part 2: Ground investigation and testing* and the often ambiguous defining of strength-related parameters is not necessary.

Chapter 17. Analysis of horizontal bearing capacity of a single pile

The objective of this chapter is to explain the use of the GEO 5 –PILE program for the analysis of horizontal bearing capacity of a single pile.

Problem specification:

The general problem specification is described in the previous chapter (*13. Pile foundations – Introduction*). Carry out all calculations for the horizontal bearing capacity of a single pile as a follow-up to the previous problem presented in chapter *14. Analysis of vertical load-bearing capacity of a single pile*. The resultant of loading components $N_1, M_{y,1}, H_{x,1}$ acts at the pile head level. Calculate pile dimensions in accordance with EN 1992-1.



Problem specification chart – single pile

Solution:

We will apply the GEO 5 – PILES program to the analysis of this problem. In the text below we will describe the solution to this example step by step.

The laterally loaded pile is analysed by the Finite Element Method as a beam resting on an elastic Winkler medium. Parameters of soils along the pile length are characterised by the modulus of horizontal reaction of subsoil.

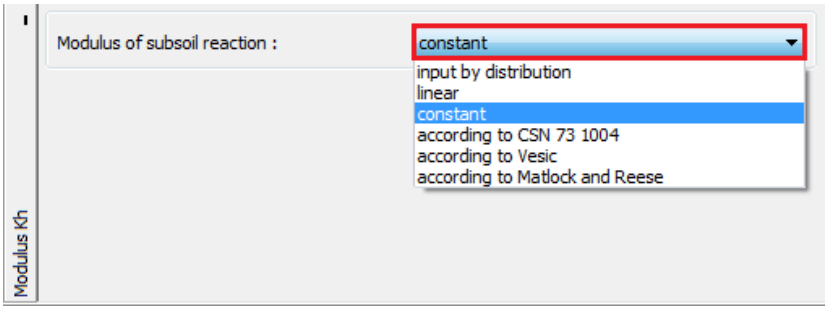
The program contains more possibilities how to determine the modulus of reaction of subsoil. Methods with linear course (Linear, Matlock and Reese) are suitable for cohesionless soils, whilst methods with constant course (Constant, Vesic) are rather for cohesive soils. The calculation method for the modulus k_h in accordance with CSN 73 1004 combines both approaches.

In the first part of this chapter we will carry out the calculation using the constant modulus of reaction of subsoil; in the second part we will compare differences existing when other methods are used.

Specification definition:

The general analysis settings, values of specified loads and the geological profile including basic strength-related parameters of soils remain unchanged.

We will choose the "constant" modulus in the „Modulus k_h" frame.



„Modulus k_h" frame

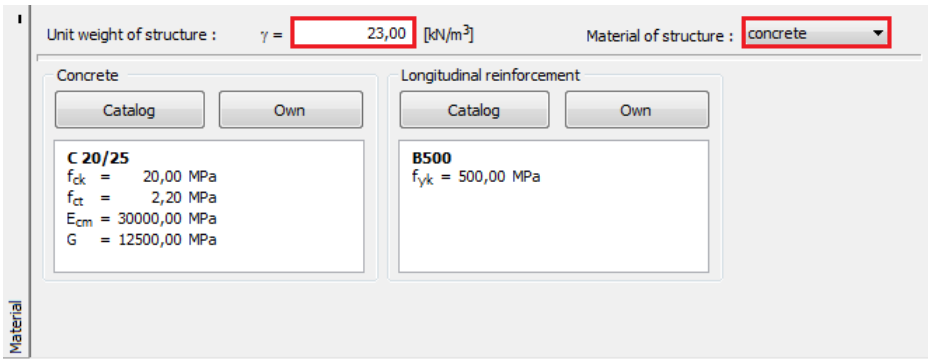
Note: The constant course of the modulus of horizontal reaction of subsoil depends on the modulus of deformation of soil $E_{def}\,[MPa]$ and the reduced pile width $r\,[m]$ (for more details visit Help – F1).

Subsequently, in the parameters of soils, we will set the value of the angle of dispersion $\beta\,[-]$ within the range $\frac{\varphi_{ef}}{4} - \varphi_{ef}$. This coefficient is therefore determined relative to the internal soil friction angle size (for more details visit Help – F1).

Soil (Soil classification)	Unit weight $\gamma\,[kN/m^3]$	Angle of internal friction φ_{ef} [°]	Angle of dispersion β [°]	Type of soil
CS – Sandy clay, firm consistency	18,5	24,5	10,0	Cohesive
S-F – Sand with trace of fines, medium dense soil	17,5	29,5	15,0	Cohesionless

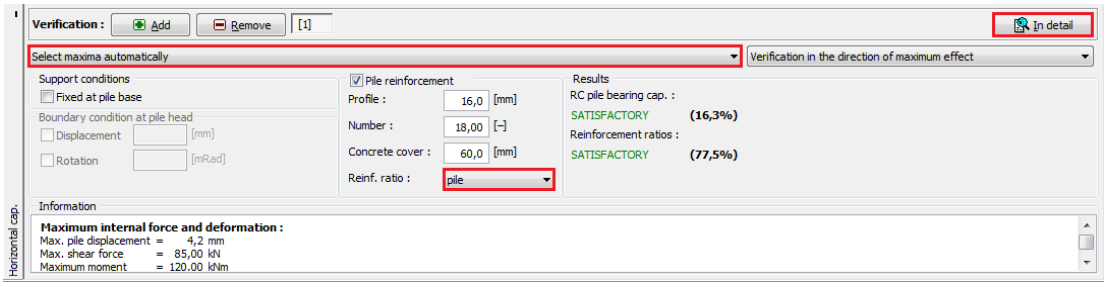
Table with the soil parameters – Horizontal bearing capacity of single pile

In the "Material" frame, we will specify the pile characteristics – the unit weight of the structure, the concrete type used and longitudinal concrete reinforcement for the dimensioning of the pile shaft.



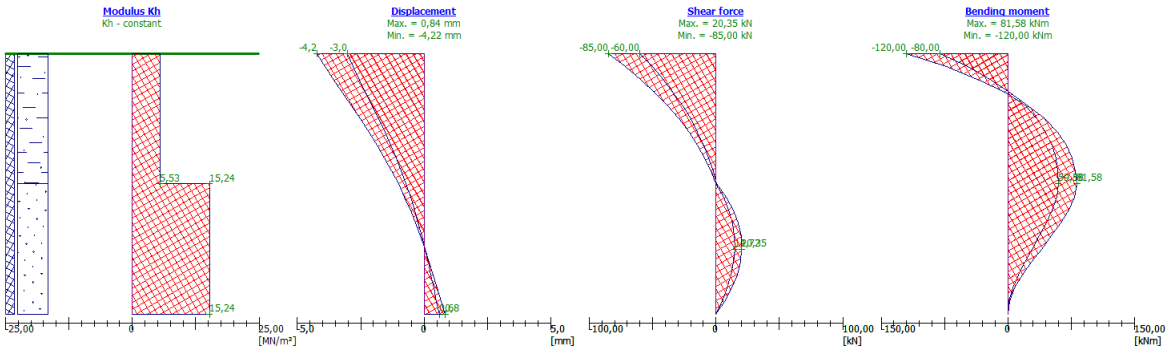
„Material" frame

Now we will go over to the "Horizontal capacity" frame, where we determine the value of the maximum horizontal deformation at the pile head, the course of the internal forces along the pile length and results of the pile dimensioning for the assessment of concrete reinforcement in the direction of the maximum effect.



„Horizontal bearing capacity" frame – Assessment for constant course of modulus k_h

Note: The boundary condition for the pile fixing at the pile base is modelled first of all in the cases of end-bearing piles with bases in hard rock or semi-rock sub-grade (it is not this case). The boundary conditions at pile head are applied when the so-called deformation load is used, where only the angular rotation and deformation at pile head are set in the program, without setting the force load (for more details visit Help – F1).



Constant course of the modulus of horizontal reaction of subsoil k_h, internal forces along the pile length

In this frame we will carry out dimensioning of the pile reinforcement. We will design longitudinal structural reinforcement – **18 pcs Ø 16 mm** and minimum concrete cover of **60 mm,** corresponding to the environmental exposure grade XC1.

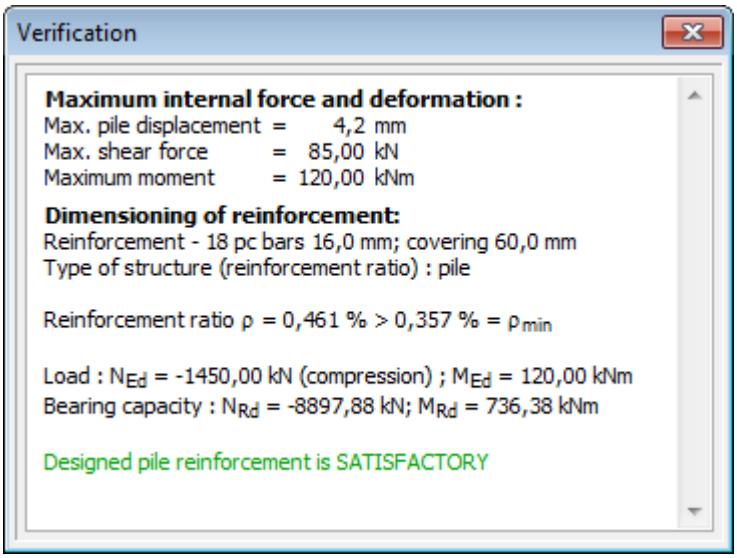
In the case being solved we consider the reinforcement ratio for the laterally loaded single pile in accordance with *CSN EN 1536: Execution of special geotechnical works - Bored piles* (Table 4 – Minimum reinforcement of bored piles). This possibility is set in the program as the "Pile".

Cross-sectional area of the pile: $A_c\ [m^2]$	Area of longitudinal reinforcement: $A_s\ [m^2]$
$A_c \leq 0.5\ m^2$	$A_s \geq 0.5\ \% \cdot A_c$
$0.5\ m^2 < A_c \leq 1.0\ m^2$	$A_s \geq 0.0025\ m^2$
$A_c > 1.0\ m^2$	$A_s \geq 0.25\ \% \cdot A_c$

„EN 1536: Table 4 – Minimum reinforcement of bored piles"

Note: It is better for compressed elements to use the reinforcement ratio as if it is for a "column", whilst a "beam" is better for piles subjected to bending. For a combination of vertical and lateral loading the CSN EN 1536 prescribes the minimum reinforcement ratio for bored piles corresponding to the proportion of the reinforcement sectional area to concrete area (for more details visit Help – F1).

We observe the use of the bending-subjected pile cross-section and the condition for the minimum reinforcement ratio in the pile dimensioning results.



Dialogue Window – „Verification (detailed)"

Analysis results

Within the framework of the assessment of the laterally loaded single pile, we are interested in the courses of internal forces along the pile length, the maximum deformations and the use of the pile cross-section. For the **constant course** of the modulus of horizontal reaction of subsoil k_h the resultant values are as follows:

- Maximum pile deformation: $u_{max} = 4.2\ mm$.
- Maximum shear force: $Q_{max} = 85.0\ kN$.
- Maximum bending moment: $M_{max} = 120.0\ kNm$.
- RC pile bearing capacity: 16.3 % SATISFACTORY.
- Pile reinforcement ratio: 77.5 % SATISFACTORY.

Comparison of results of various methods of the determination of the modulus of subsoil reaction

The values and course of the modulus of horizontal reaction of subsoil k_h vary depending on different analysis methods used and input soil parameters, which affect it:

- CONSTANT: angle of dispersion $\beta\,[–]$,
- *LINEAR (Bowles)*: angle of dispersion $\beta\,[–]$,
  coefficient $k\,[MN/m^3]$ according to the soil type,
- *According to CSN 73 1004*: cohesive, or cohesionless soil,
  Modulus of horizontal compressibility $n_h\,[MN/m^3]$,
- *According to VESIC*: modulus of elasticity $E\,[MPa]$.

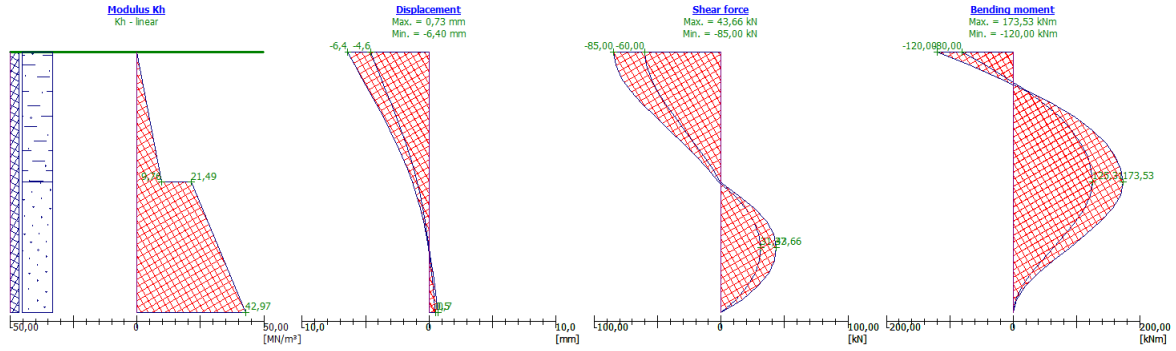
In this calculation, we will set input values in the program using Help (see F1) as follows:

Modulus of subsoil reaction $k_h\,[MN/m^3]$	Angle of dispersion $\beta\,[–]$	Coefficient $k\,[MN/m^3]$	Modulus of elasticity $E\,[MPa]$	Modulus of horizontal compressibility $n_h\,[MN/m^3]$
CONSTANT	10 – CS	---	---	---
	15 – S-F			
LINEAR (Bowles)	10 – CS	60 – CS	---	---
	15 – S-F	150 – S-F		
CSN 73 1004	Cohesive soil – CS, firm consistency			---
	Cohesionless soil – S-F, medium dense			4,5
VESIC	---	---	5,0 – CS	---
			15,5 – S-F	

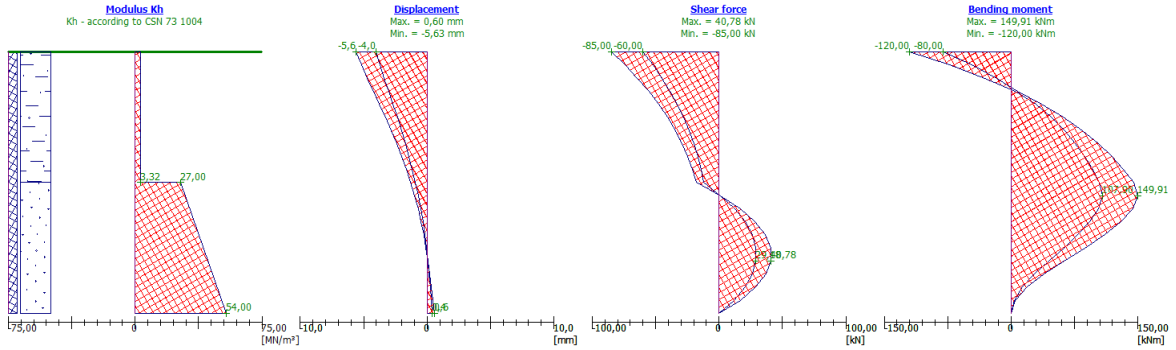
Summary table of soil parameters for horizontal bearing capacity of single pile

Now we will get back to the setting of input data; we will always change the respective method of the calculation of the modulus of horizontal reaction of subsoil and then we will add remaining parameters of soils. We will carry out the procedure for the following methods:

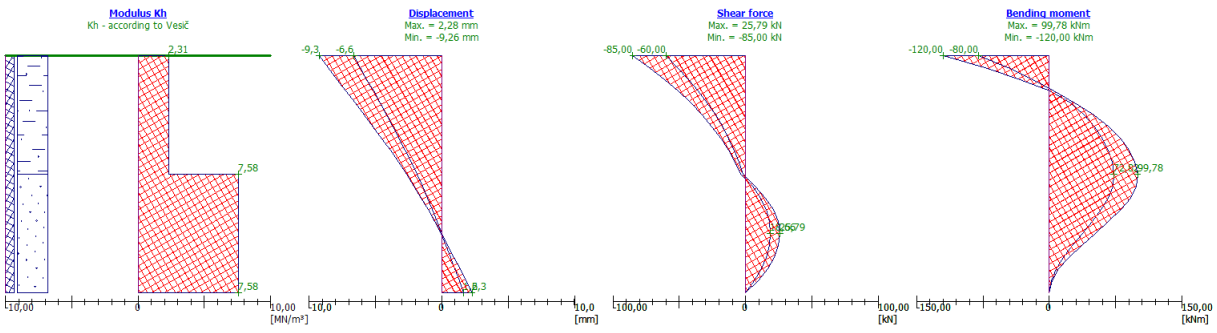
- using the linear course (according to Bowles),
- according to CSN 73 1004,
- according to Vesic.



Linear course of the modulus of horizontal reaction of subsoil k_h, internal forces



Course of modulus of subsoil reaction k_h according to CSN 73 1004, internal forces



Course of modulus of horizontal reaction of subsoil k_h according to Vesic, internal forces

Results of the analysis of horizontal bearing capacity of single pile:

The results of the analysis of horizontal bearing capacity of a single pile relative to the method used for the calculation of the modulus of horizontal reaction of subsoil k_h are presented in the following table:

Modulus of subsoil reaction k_h $[MN/m^3]$	Max. pile displacement u_{max} $[mm]$	Max. bending moment M_{max} $[kNm]$	RC pile bearing capacity [%]
CONSTANT	4.2	120.0	16.3
LINEAR (Bowles)	6.4	173.53	18.1
CSN 73 1004	5.6	149.91	17.3
VESIC	9.3	120.0	16.3

Summary of results – Horizontal bearing capacity and dimensioning of single pile

Conclusion:

It follows from the calculation results that the observed values of internal forces along the pile length and the maximum deformations at the pile head are slightly different, but the influence of the chosen method of the modulus of subsoil reaction calculation is not crucial.

Chapter 18. Analysis of vertical load bearing capacity and settlement of a pile group

The objective of this chapter is to explain the application of the GEO 5 – PILE GROUP program.

Introduction

Analyses in the Pile Group program can be divided into two groups:

- Spring Method,
- analytical solutions.

The Spring Method makes the calculation of the deformation of the entire pile foundation and determination of internal forces along the lengths of individual piles possible. Loading is defined as a general spatially acting combination of $N, M_x, M_y, M_z, H_x, H_y$. An important result is rotation and displacement of the rigid pile cap and further the dimensioning of the reinforcement cage for individual piles. The Spring Method is dealt with in the following chapter 19. *Analysis of deformation and dimensioning of a pile group*.

The analytical solution is intended for analysing vertical bearing capacity of a pile group loaded solely by a vertical normal force. The analysis result comprises the vertical bearing capacity of the pile foundation and the average settlement of the pile.

The analytical solution is further divided according to the soil type:

- for cohesive soils,
- for cohesionless soils.

The vertical bearing capacity of a pile group in **cohesive soil** is considered to be in undrained conditions. It is determined as the bearing capacity of an earth body in the form of a prism drawn around the pile group according to the FHWA. Only the total soil cohesion (undrained shear strength) c_u is specified for the analysis purpose.

The settlement of a pile group in cohesive soil (in undrained conditions) is based on the calculation of the settlement of a substitute spread foundation (the so-called *consolidation settlement of pile group* or, abbreviated, the *2:1 method).*

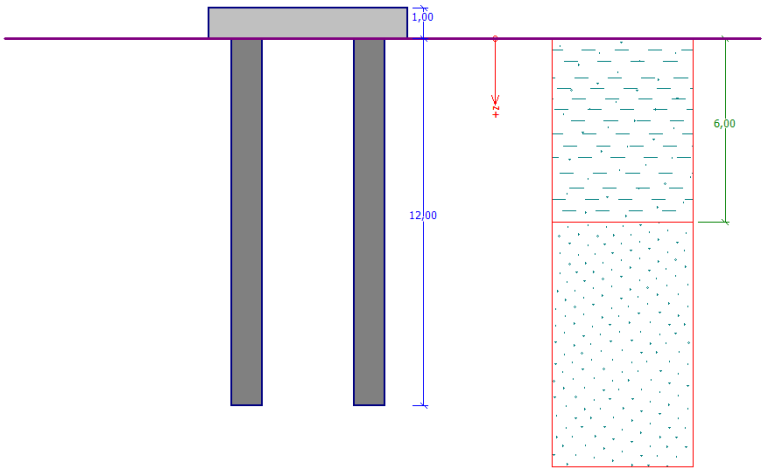
For the purpose of this pile group settlement assessment the analysis incorporates the influence of the foundation depth and of the thickness of the deformation zone according to the methodology for assessing the settlement of spread foundations. It is possible in the Czech and Slovak Republics to apply the procedure according to *CSN 73 1001 – Ground under spread foundations* to the analysis of pile group settlement.

The assessment of a pile group in **cohesionless soil** is based on procedures identical with those used for the analysis of a single pile in **cohesionless soil** (chapter *14. Analysis of vertical load-bearing capacity of a single pile*). The only introduced addition is the so-called efficiency of pile group reducing the total vertical bearing capacity of pile foundation.

The loading curve for a pile group in cohesionless soil is constructed in the same way as the curve for a single pile (chapter *15. Analysis of single pile settlement*) according to Prof. H. G. Poulos, with the exception of the total settlement of the pile group, which is increased by the so-called group settlement factor g_f, which allows for the group effect of individual piles. The extent of this parameter depends on the geometrical arrangement of the pile group.

Problem specification:

The general problem specification is described in the previous chapter (*13. Pile foundations – Introduction*). Carry out all calculations for the vertical bearing capacity of a pile group in accordance with EN 1997-1 (DA 2) relative to the problem *14. Analysis of vertical load-bearing capacity of a single pile.* The resultant of the total loading comprising N, M_y, H_x acts at the upper base of the pile cap, just in its centre.



Problem specification chart – pile group

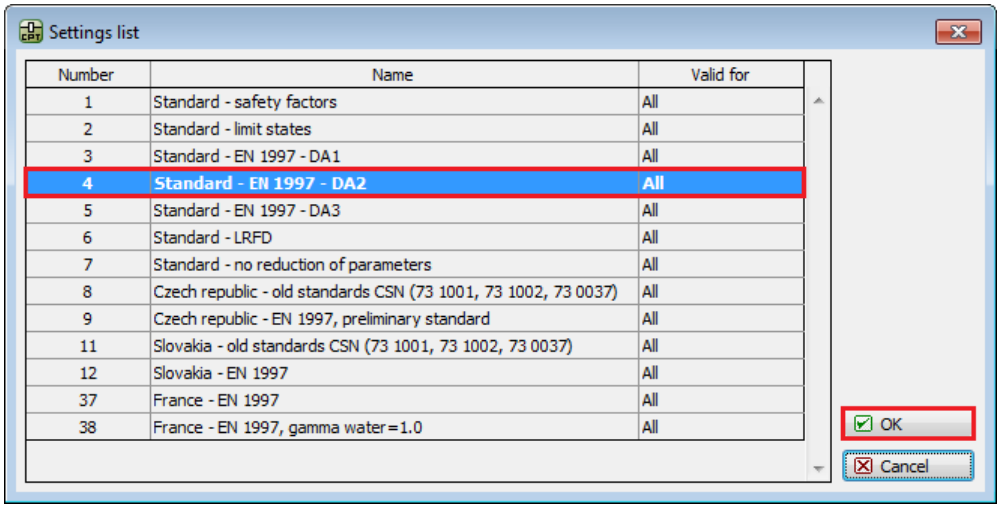
Solution:

We will use the GEO 5 – PILE GROUP program for this problem analysis. For the problem simplification and acceleration of the setting of general problem parameters (the design, soil, assigning and the profile) we will use the possibility of importing data from the problem 14. *Analysis of vertical load-bearing capacity of a single pile*.

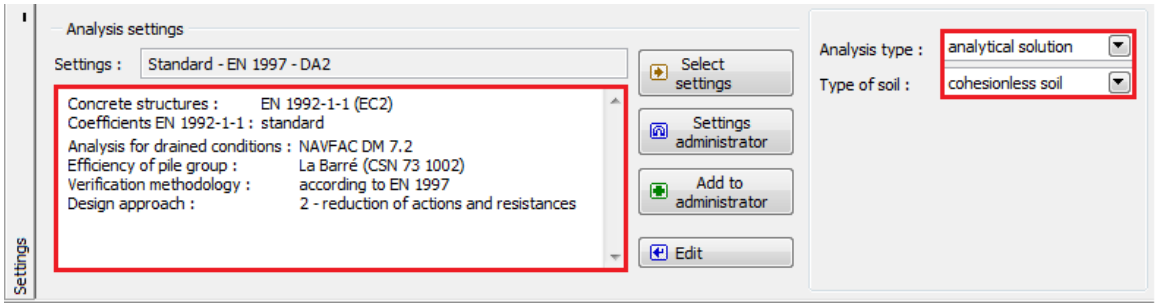
In this analysis we will assess the pile group according to analytical calculation methods (NAVFAC DM 7.2, EFFECTIVE STRESS a CSN 73 1002) identical with those applied to a single pile. We will focus ourselves on other input parameters affecting the overall results.

Specification procedure:

In the „Settings“ frame we will click on the “Setting list” button and then we will choose the „Standard – EN 1997 – DA2“calculation setting. We will maintain the calculation system using the *analytical solution*. In our particular case we will consider the type of soil to be ***cohesionless soil*** because we will assess the piles in *drained conditions*.

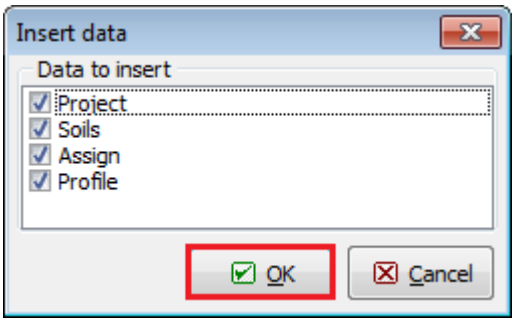


Dialogue window „Setting list“



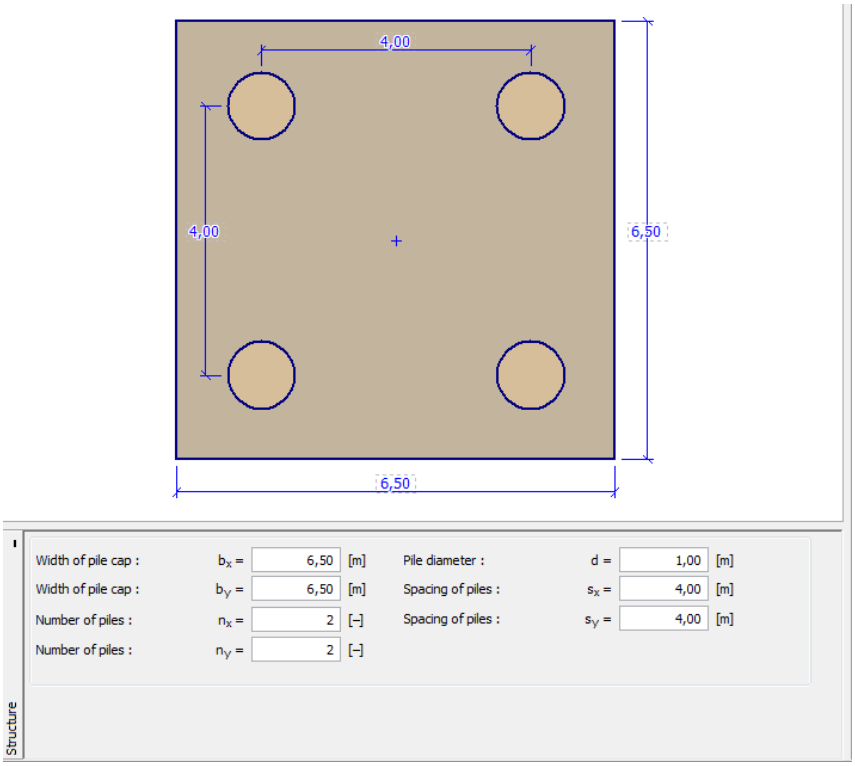
„Settings” frame

We will use the possibility of importing the data, avoiding the necessity of setting all input data again. We will start to solve the problem *14. Analysis of vertical bearing capacity of a single pile* in the GEO 5 – Piles program; on the upper tool bar we will click on the "Edit" button and then we will select the "Copy data" option. Subsequently, in the GEO 5 – Pile Group in the file being edited by us, we will again click on the "Edit" button on the upper tool bar and choose the "Paste data" option. Through this step the data required for the analysis will be transferred and a significant part of the work with inserting input data will be facilitated.



Dialogue window „Insert data"

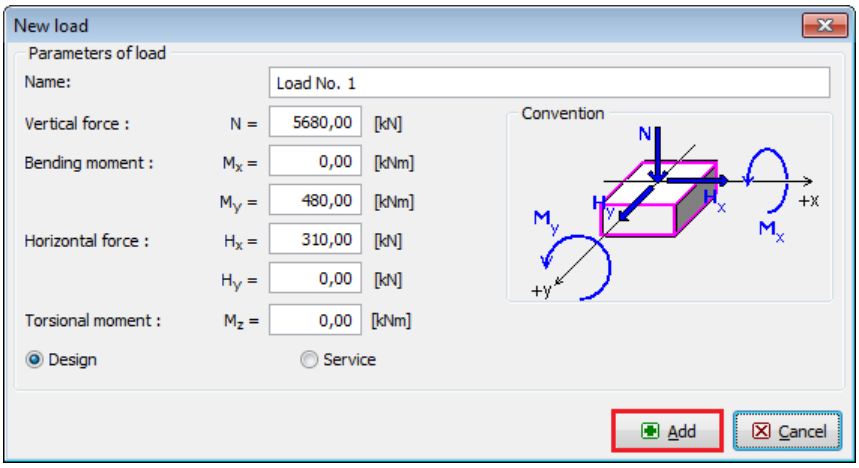
Now we will go over to the "Structure" frame. We will specify ground plan dimensions of the base slab (the pile cap), the number of piles in the group, their diameter and spacing on centres (between piles in direction x, or y).



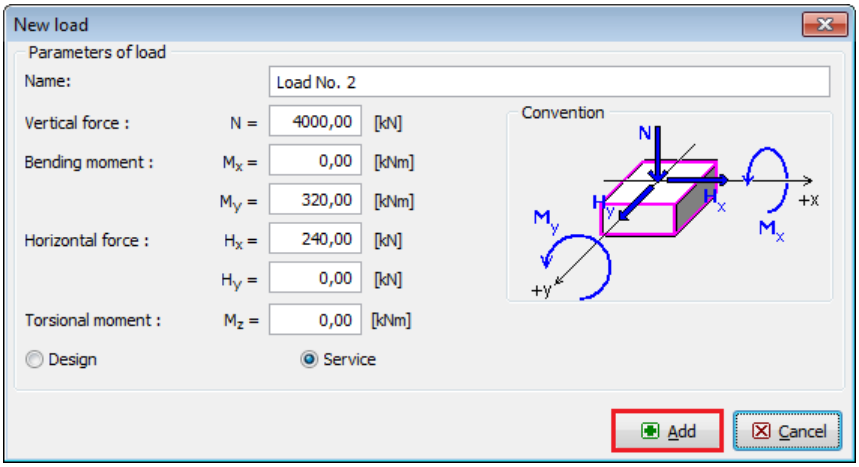
„Structure" frame

Subsequently, in the "Geometry" frame, we will define the depth from ground surface, the pile head offset, the pile cap thickness and the lengths of all piles in the group. Individual piles in the group have equal diameters and lengths.

In the "Material" frame we will specify the unit weight of the structure $\gamma = 23.0\ kN/m^3$. Subsequently we will define the loading. The pile group vertical bearing capacity is analysed using design loads, whilst service load is used for the settlement analysis.



Dialogue window „New load" – Design (calculation) load



Dialogue window „New load" – service (imposed) load

We will carry out the pile group assessment in the "Vertical capacity" frame. To meet the condition of reliability, value R_g must be bigger than the magnitude of the acting design load V_d (for more details visit Help – F1). For the **NAVFAC DM 7.2** analysis method and the pile group efficiency *La Barré* (CSN 73 1002) according to the initial analysis settings, the results of the vertical bearing capacity of the pile group are as follows:

– ***La Barré*** (CSN 73 1002): $\eta_g = 0.84$.

$R_g = 7491.90\ kN > V_d = 6991.86\ kN$ … Satisfactory.

Note: The calculated vertical bearing capacity of a pile group in cohesionless soil must be reduced because individual piles statically affect each other. The assessment in the program contains several methods of determining the pile group efficiency η_g. *This dimensionless figure (usually within the range 0.5 to 1.0) reduces the pile group total vertical bearing capacity* R_g *with respect to*:

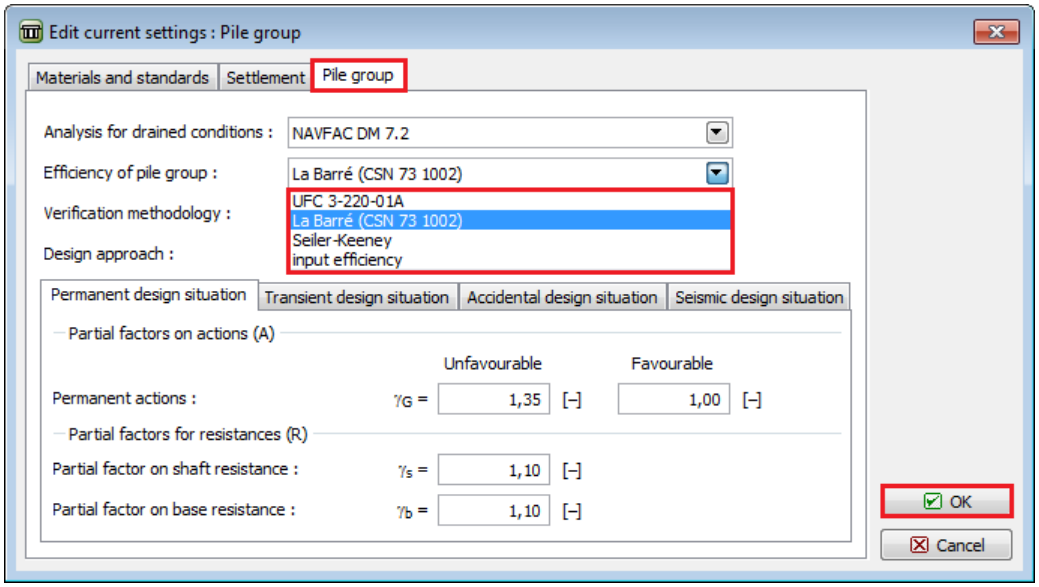
– *the number of piles in group* n_x, n_y;

– *the spacing of piles in group on centres* s_x, s_y;

– *the diameter of piles in group* d.

The pile group efficiency η_g *depends solely on the set pile group geometry, not on the analysis method.*

Further we can check the vertical bearing capacity even for other methods of the determination of pile group efficiency η_g. We will go over back to the "Settings" frame. We will click on the "Edit" button at the bottom left of the screen and will select step by step remaining possibilities „UFC 3-220-01A", or „Seiler-Keeney" in the "Pile group" tab sheet.



Dialogue window „Edit current settings"

For the other analysis methods, the procedure in the program is analogical with the problem solution *14. Analysis of vertical bearing capacity of a single pile*.

The results of the analysis of the vertical bearing capacity of a pile group in cohesionless soil (i.e. in drained conditions) relative to the method used and the pile group efficiency η_g are presented in the following table:

- ***La Barré*** (CSN 73 1002): $\eta_g = 0.84$,
- ***UFC 3-220-01A***: $\eta_g = 0.80$,
- ***Seiler-Keeney***: $\eta_g = 0.99$.

EN 1997-1, DA2 (cohesionless soil) Analysis method	Efficiency of pile group η_g $[-]$	Bearing capacity of single pile R_c $[kN]$	Bearing capacity of pile group R_g $[kN]$
NAVFAC DM 7.2	0.84	2219.06	7491.90
	0.80		7100.98
	0.99		8829.18
EFECTIVE STRESS	0.84	6172.80	20 840.41
	0.80		19 572.96
	0.99		24 560.34
CSN 73 1002	0.84	5776.18	19 501.36
	0.80		18 483.79
	0.99		22 982.28

Summary of results – Vertical bearing capacity of pile group in drained conditions

Conclusion (vertical capacity of pile group):

The calculated vertical bearing capacity of pile group R_g in cohesionless soil must be reduced (using the so-called pile group efficiency η_g) because individual piles statically affect each other. It applies in general that individual piles in a group affect each other more with the spacing on centres decreased.

The designer should always carefully consider whether to use the calculation in drained or undrained conditions for the analytical solution to vertical bearing capacity of pile group. The two calculation types are significantly different.

Analysis of pile group settlement

The analysis of the pile group settlement is completely identical with that applied to a single pile, the calculated settlement is in addition multiplied by the group settlement factor g_f.

Note: The extent of the group settlement factor g_f depends on the geometrical arrangement of the pile group, i.e. the diameter of piles in the group and the width of the pile cap.

The analysis results are presented in the following table:

Analysis method of vertical bearing capacity of pile group	Load at the onset of mobilization of skin friction R_{yu} $[kN]$	Settlement of pile group s $[mm]$ for force $V = 4000$ kN
NAVFAC DM 7.2	3184,47	34,8
EFECTIVE STRESS	7274,43	15,3
CSN 73 1002	8057,77	15,3

Summary of results – Settlement of pile group according to Poulos

Conclusion (pile group settlement):

It follows from the analysis results that the vertical bearing capacity of a pile group is different as far as the total settlement is concerned. The analysis of the pile group settlement in cohesionless soil (drained conditions) is based on the linear settlement theory, for which the basic input data required for the settlement calculation comprises the values of skin friction R_s and the resistance on pile base R_b.

In contrast, the settlement of a pile group in cohesive soil (undrained conditions) is based on the calculation for a substitute spread foundation. In the world this calculation method is titled the so-called *consolidation settlement of a pile group* or, abbreviated, *the 2:1 method.* For this pile group settlement assessment, the effect of the depth from ground surface and the deepness of deformation zone in accordance with the methodology for assessing the settlement of spread foundations is introduced into the calculation.

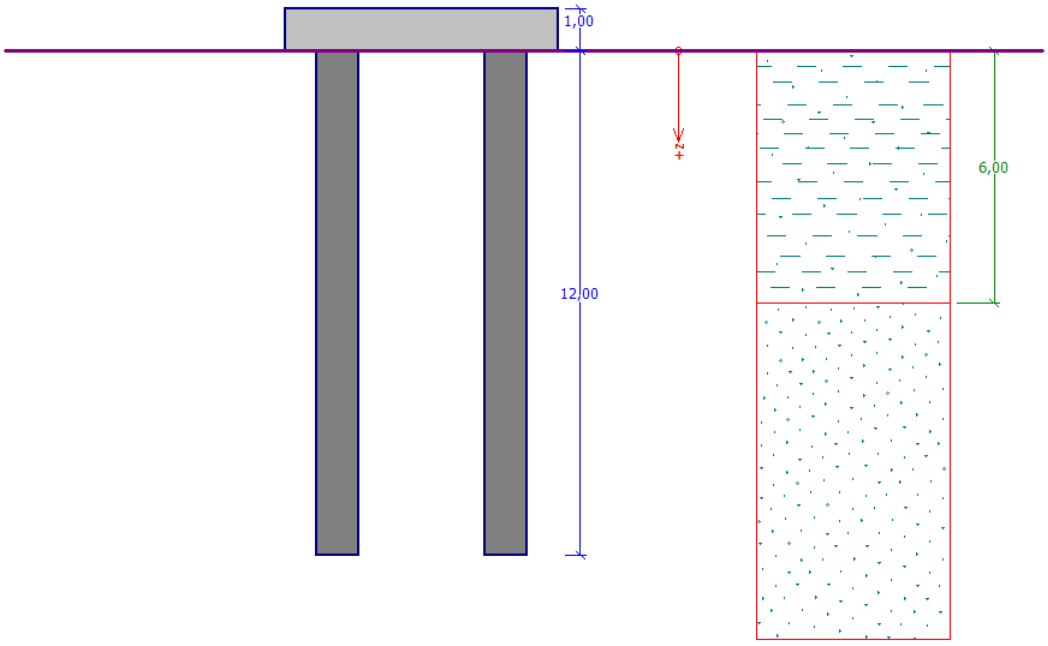
The two calculation methods significantly differ and provide absolutely different results. GEO 5 program authors recommend that vertical bearing capacity and settlement of a pile group should be calculated according to local customs.

Chapter 19. Analysis of deformation and pile group dimensioning

The objective of this chapter is to explain the application of the GEO 5 – PILE GROUP program to the analysis of angular rotation and displacement of a stiff pile cap, to the determination of internal forces along the lengths of individual piles and to the pile cross-sections dimensioning.

Problem specification:

General problem specification is described in the previous chapter (*13. Pile foundations – Introduction*).). All analyses of the vertical load-bearing capacity of a pile group shall be carried out relative to the previous problem *18. Analysis of vertical bearing capacity and settlement of pile group.* The resultant of the total load comprising N, M_y, H_x acts at the upper base of the pile cap, just in its centre. The dimensioning of piles in the group shall be carried out in accordance with standard EN 1992-1-1 (EC 2), using standard values of partial coefficients.



Problem specification chart – pile group

Solution:

To solve this problem we will use the GEO 5 – PILE GROUP program. For the problem simplification and acceleration of the setting of general problem parameters we will use all input data from the problem *18. Analysis of vertical load-bearing capacity of pile group* (e.g. by means of data importing).

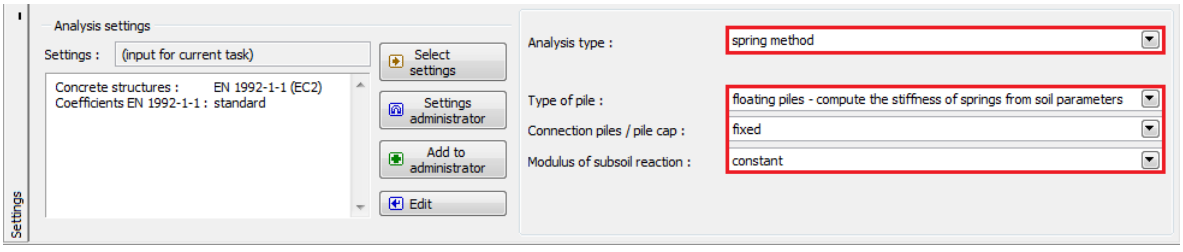
We will analyse the pile group according to the so-called *Spring Method*, which models individual piles as beams on an elastic bed. Each pile is internally divided into ten sections, for which the values of horizontal and vertical springs are computed. The base slab (pile cap) is considered to be infinitely stiff. The solution itself is carried out using the deformation variant of the Finite Element Method.

Specification procedure:

We will change the analysis type in the "Settings" frame to the "Spring method" option. We will consider the connection of piles to the base slab to be ***stiff, i.e. fixed***. It is assumed for this boundary condition that the bending moment will be transferred in the pile heads.

For the pile bearing at the base we will select the "floating piles – compute the stiffness of springs from soil parameters" option.

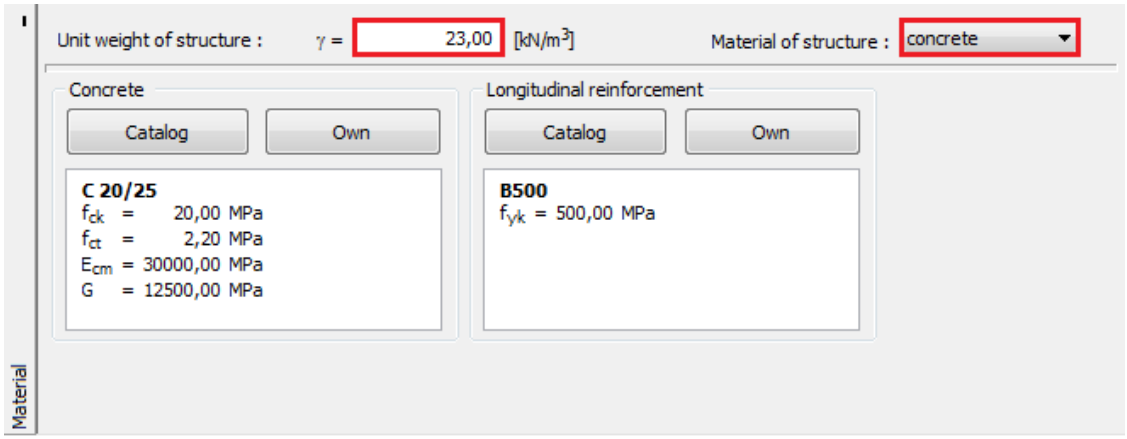
Note: The program makes several options for boundary conditions for the pile bearing in vertical direction possible. For end-bearing piles, or piles keyed into bedrock, the vertical stiffness of springs is not specified – the pile base is modelled as a joint or a sliding joint. For floating piles, it is necessary to define the sizes of vertical springs, both on the skin and then on the pile base. The program makes specifying of the size of springs possible, but it is mostly reasonable to select the "compute the size of springs" option. In this case the program computes the springs from deformational properties of soils for the typical load set (for more details visit Help – F1).



„Analysis settings" frame – spring method

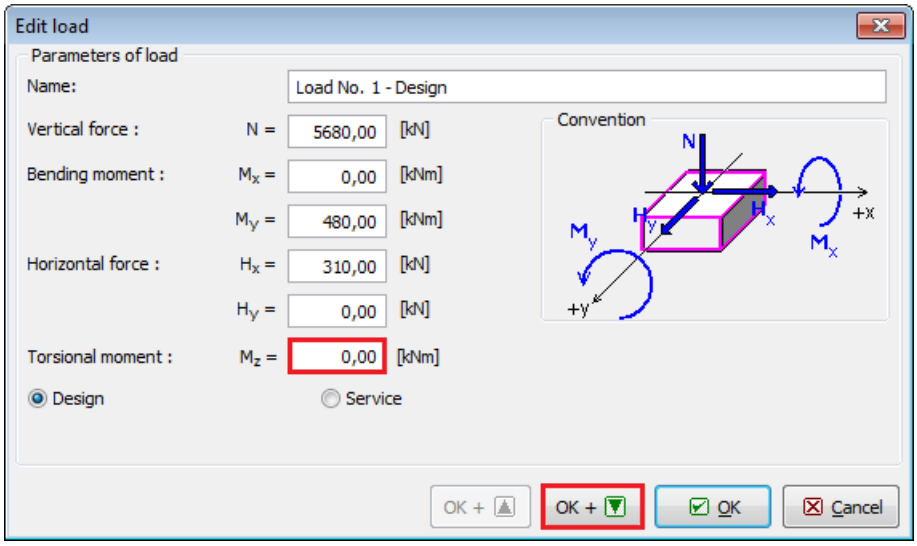
The horizontal modulus of subsoil reaction characterises the pile behaviour in the lateral direction. For this analysis we will consider the modulus k_h (inclusive of parameters affecting its magnitude) to be identical with that used in the single pile solution (see Chapter *17. Analysis of horizontal bearing capacity of a single pile).* In the opening part of this chapter we will carry out the analysis using the constant modulus of subsoil reaction and, in the second part, we will compare the differences between the results when other methods are used (linear – according to Bowles, according to CSN 73 1004 and according to Vesic).

In the "Material" frame we will specify characteristics of individual piles in the group, i.e. the unit weight of the structure, the concrete type used and longitudinal concrete reinforcement for the dimensioning of the pile shaft.

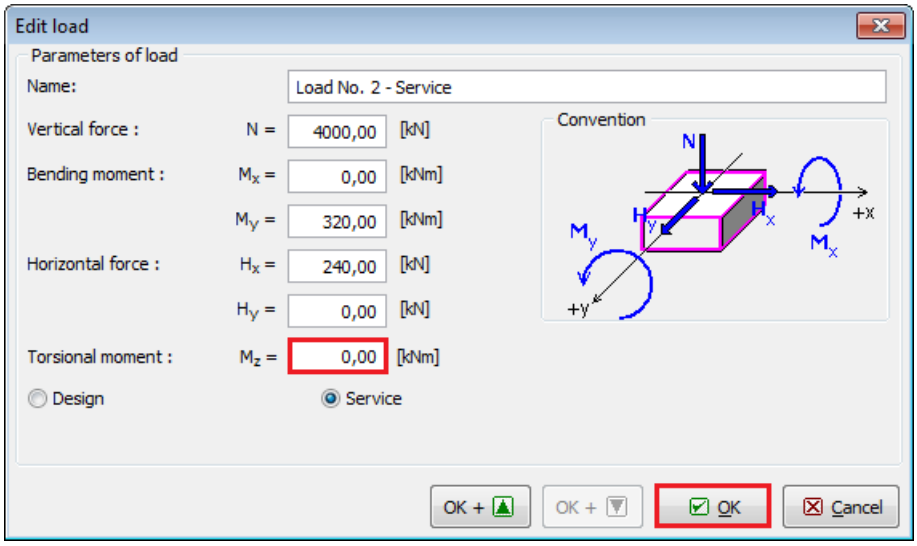


„Material" frame

Subsequently we will define the load. Design load is applied to the dimensioning of individual piles in the group and the determination of the internal forces curves, whilst service load is used for the calculation of deformations.

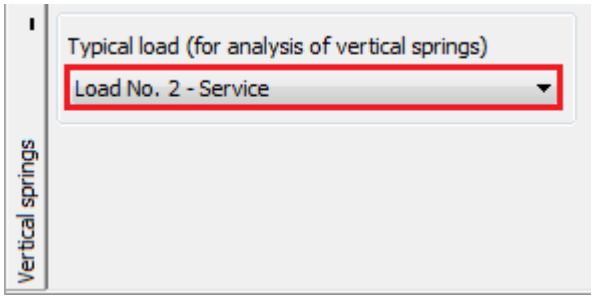


Dialogue window „Edit load“ – Design load



Dialogue window „Edit load“ – Service load

In the “Vertical springs” frame we will select the so-called typical load, which is used for the calculation of the stiffness of vertical springs. In our case we will choose the “Load No. 2 – Service” option.



„Vertical springs” –Typical load

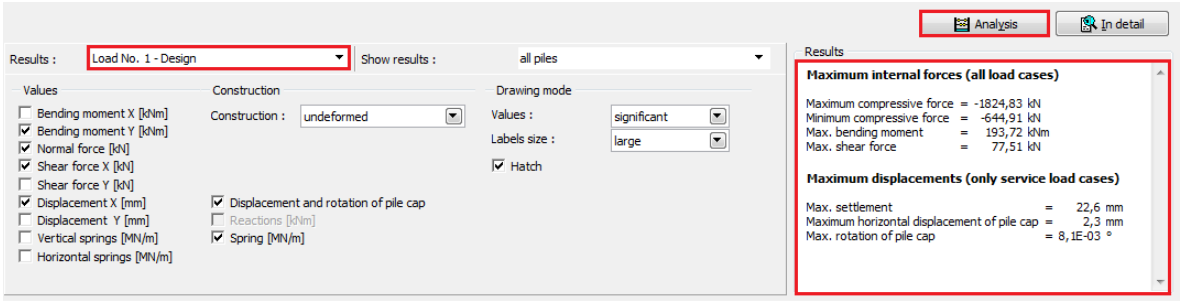
Note: In the case of the Typical load option, the service (characteristic) load should be applied, which best characterises the structure behaviour (for more details visit Help – F1). The procedure for the computation of the vertical springs is as follows:

a) *The calculated load is distributed among individual piles.*
b) *The size of vertical springs on the pile skin and at the base is determined for individual piles, depending on the load and soil parameters.*

The effect of the load on the calculated stiffness is significant – for example, the stiffness of the spring at the base is always zero for a tensioned pile. For that reason it may be advantageous in some cases to carry out the calculation several times for various typical loads.

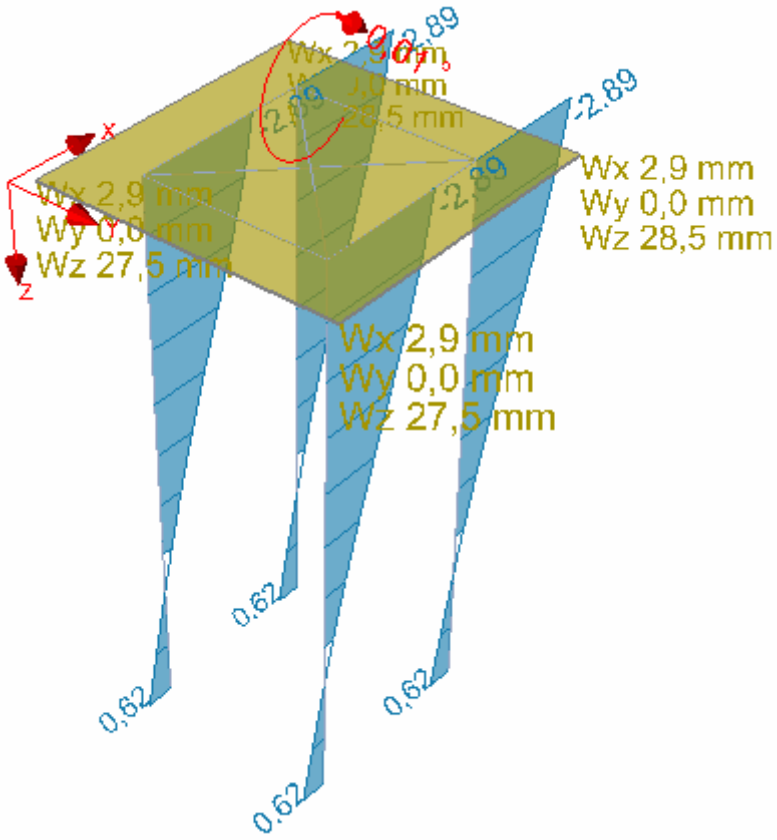
Analysis: Spring Method

In the "Analysis" frame we will carry out the assessment of the pile group for the initial settings (the **constant** modulus of subsoil horizontal reaction) and will display the results with internal force curves.



„Analysis" frame – Spring Method (constant modulus of subsoil reaction)

Note: The stiffness of piles in the group is automatically modified according to their locations. Piles on the edge and inside the group have the sizes of the horizontal stiffness and shear stiffness of springs reduced in comparison with a single pile. Springs on pile bases are not reduced (for more details visit Help – F1).



„Analysis" – Spring Method (horizontal displacement and rotation of the pile cap, deformations in the "x" direction)

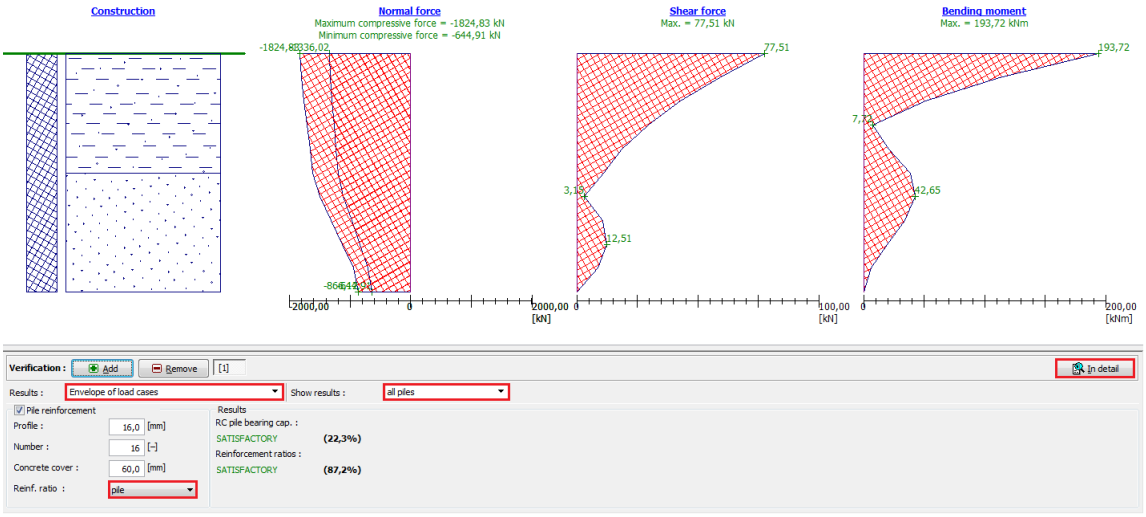
The results of the analysis for the initial settings (for maximum deformation) are as follows:

- Maximum settlement: 22.6 *mm*;
- Max. horizontal displacement of pile cap: 2.3 *mm*;
- Maximum rotation of pile cap: $8.1 \cdot 10^{-3}$ °.

Dimensioning:

Subsequently we will go over to the "Dimensioning" frame and, similarly to the chapter *5. Analysis of horizontal bearing capacity of single pile*, we will propose and assess the main structural reinforcement of the piles. We will consider identical reinforcement ratio for all piles in the group – **16 pcs Ø 16 mm** and the minimum concrete cover of **60 mm,** according to the exposure grade XC1.

The reinforcement ratio for a generally loaded pile group is in this case considered to be in accordance with CSN EN 1536:1999 (identically with that in *chapter 17*). In the program this option is set as a "pile" *(*for more details visit Help – F1).



„Dimensioning" frame – results for all piles in the group from the envelope of loading cases

We observe the utilisation of cross-section of all piles in the group in terms of bending and the condition for the minimum reinforcement ratio for the overall envelope of load cases:

- RC pile bearing capacity: 22.3 % SATISFACTORY.
- Reinforcement ratio: 87.2 % SATISFACTORY.

  ($\rho = 0.410 > \rho_{min} = 0.357$ %).

Analysis results:

The procedure in the program for other analyses is analogical with the procedure applied to the previous problems. We will always change the method of the calculation of the modulus of subsoil reaction in the "Settings" frame and will carry out the assessment of the pile group in the "Analysis" and "Dimensioning" frames. We will record the results in summary tables.

Modulus of subsoil reaction k_h $[MN/m^3]$	Compressive force (maximum, minimum) $[kN]$	Maximum bending moment $[kNm]$	Maximum shear force $[kN]$
CONSTANT	-1824.83 -644.91	193.72	77.51
LINEAR (Bowles)	-1841.04 -639.58	226.13	77.51
according to CSN 73 1004	-1835.66 -641.37	215.37	77.51
according to VESIC	-1846.38 -637.88	236.77	77.51

Summary of results (internal forces) – Verification of a pile group (spring method)

Modulus of subsoil reaction k_h $[MN/m^3]$	Maximum settlement $[mm]$	Max. horizontal displacement $[mm]$	Max. rotation of pile cap $[°]$	RC pile bearing capacity $[\%]$
CONSTANT	22.6	2.3	$8{,}1 \cdot 10^{-3}$	22.3
LINEAR (Bowles)	22.9	3.0	$1{,}3 \cdot 10^{-2}$	23.6
according to CSN 73 1004	22.8	2.9	$1{,}2 \cdot 10^{-2}$	23.2
according to VESIC	23.0	4.2	$1{,}5 \cdot 10^{-2}$	24.1

Summary of results – displacements and dimensioning of a pile group

Conclusion:

The values of the maximum settlement of the pile group, settlement displacements and the base slab rotation are within allowable limits.

It follows from the analysis results that the observed values of internal forces along the length of individual piles and the maximum deformations at pile heads in the group are slightly different, but the influence of the method selected for the calculation of the modulus of subsoil reaction k_h is not so essential.

The pile reinforcement cage proposed is satisfactory. The main condition for the reinforcement ratio of piles is also met.