Analysis of the horizontal bearing capacity of a single pile
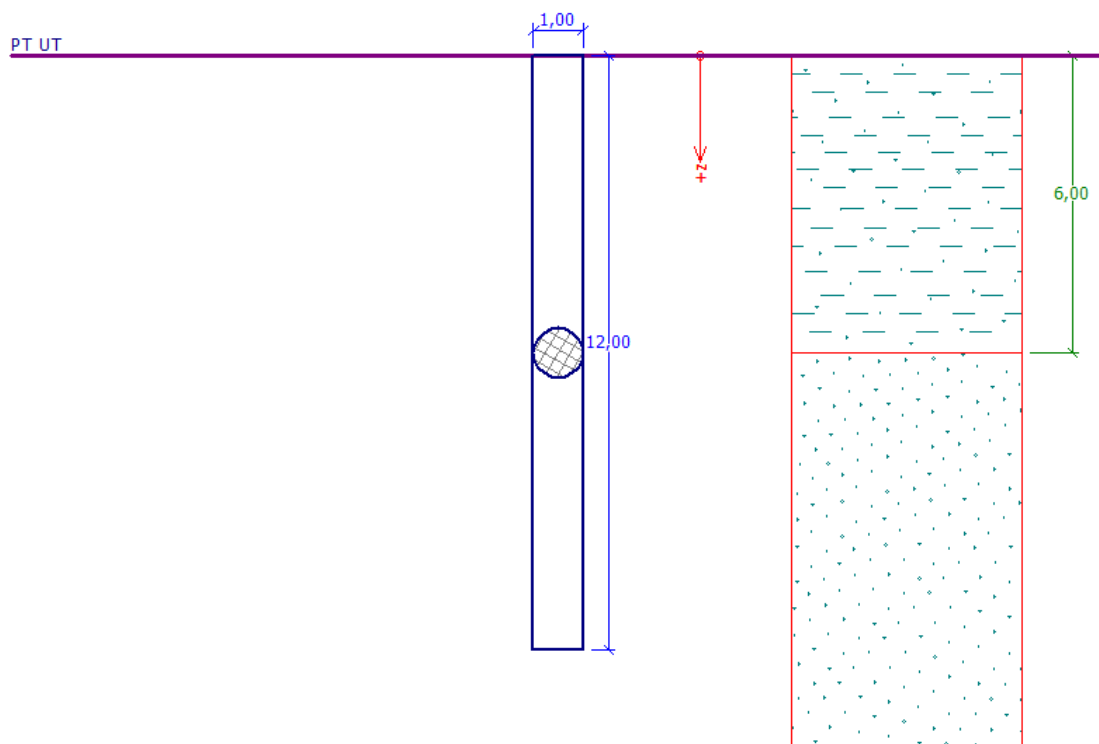
Program: Pile

Soubor: Demo_manual_16.gpi

The objective of this engineering manual is to explain how to use the GEO 5 – PILE program to analyze the horizontal bearing capacity of a single pile.

Problem specification

The general specification of the problem was described in the previous chapter (*12. Pile foundations – Introduction*). Carry out all calculations of the horizontal bearing capacity of a single pile as a follow-up to the previous problem presented in chapter *13. Analysis of vertical load-bearing capacity of a single pile*. The resultant of the 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 use the GEO 5 – PILE program to analysz this problem. In the text below, we will describe the solution to this problem step by step.

The laterally loaded pile is analyzed by the Finite Element Method as a beam resting on an elastic Winkler medium *(Elastic subsoil - p-y method)*. Parameters of the soils along the pile length are characterized by the modulus of the horizontal reaction of subsoil.
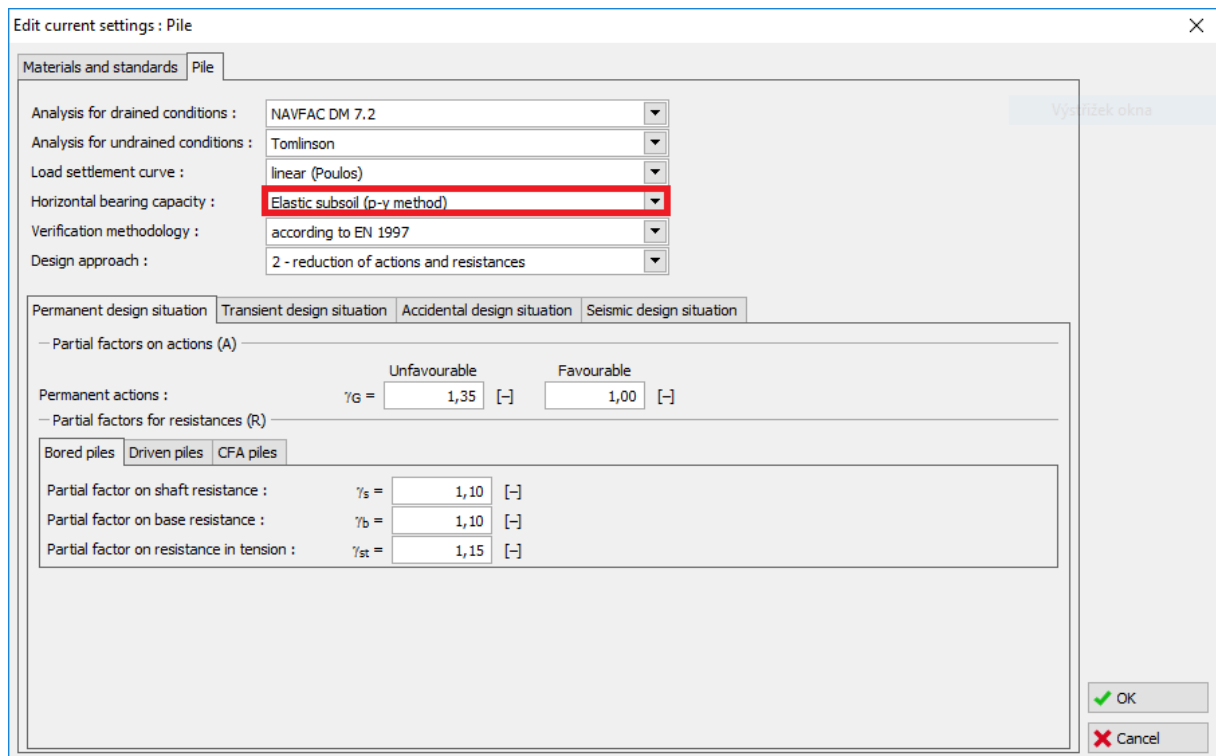
The program contains a variety of options on how to determine the modulus of the reaction of subsoil. Methods with a linear course (Linear, Matlock and Reese) are suitable for cohesionless soils, whilst methods with a constant course (Constant, Vesic) are better for cohesive soils. The calculation method for 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 the reaction of subsoil; in the second part, we will compare the differences occurring when other methods are used.

Specification definition

In the "Pile" program, open the file from manual no. 13. Firstly, in the "Settings" frame, click on the "Edit" button and check that the method of calculation of the horizontal bearing capacity is set as "Elastic subsoil (p-y method)".
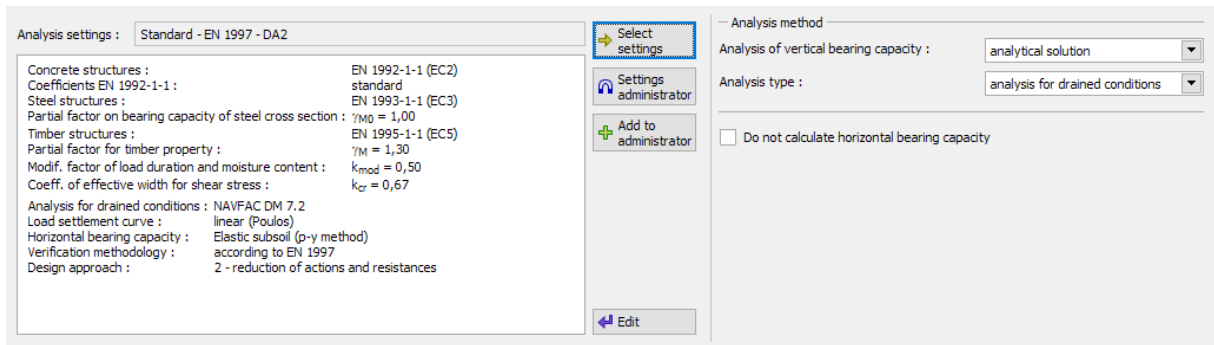
Note: For the horizontal bearing capacity analysis of a pile in homogenous soil, it is also possible to use the [Broms method](link) (for more details visit the program help – F1).
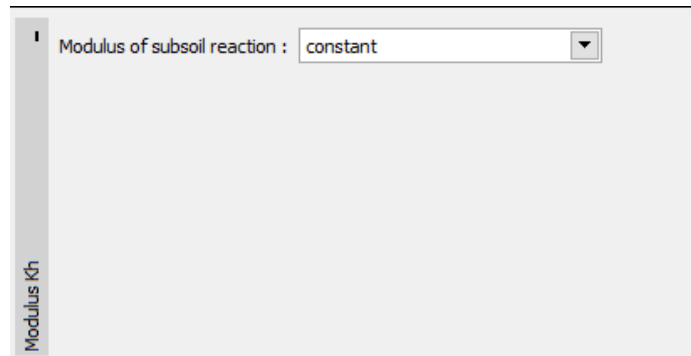
"Edit current settings" dialog window

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

In the "Settings" frame, it is also necessary to uncheck the option "Do not calculate horizontal bearing capacity".

"Settings" frame

Then move on to the "Modulus Kh" frame, where we will choose the "constant" modulus.
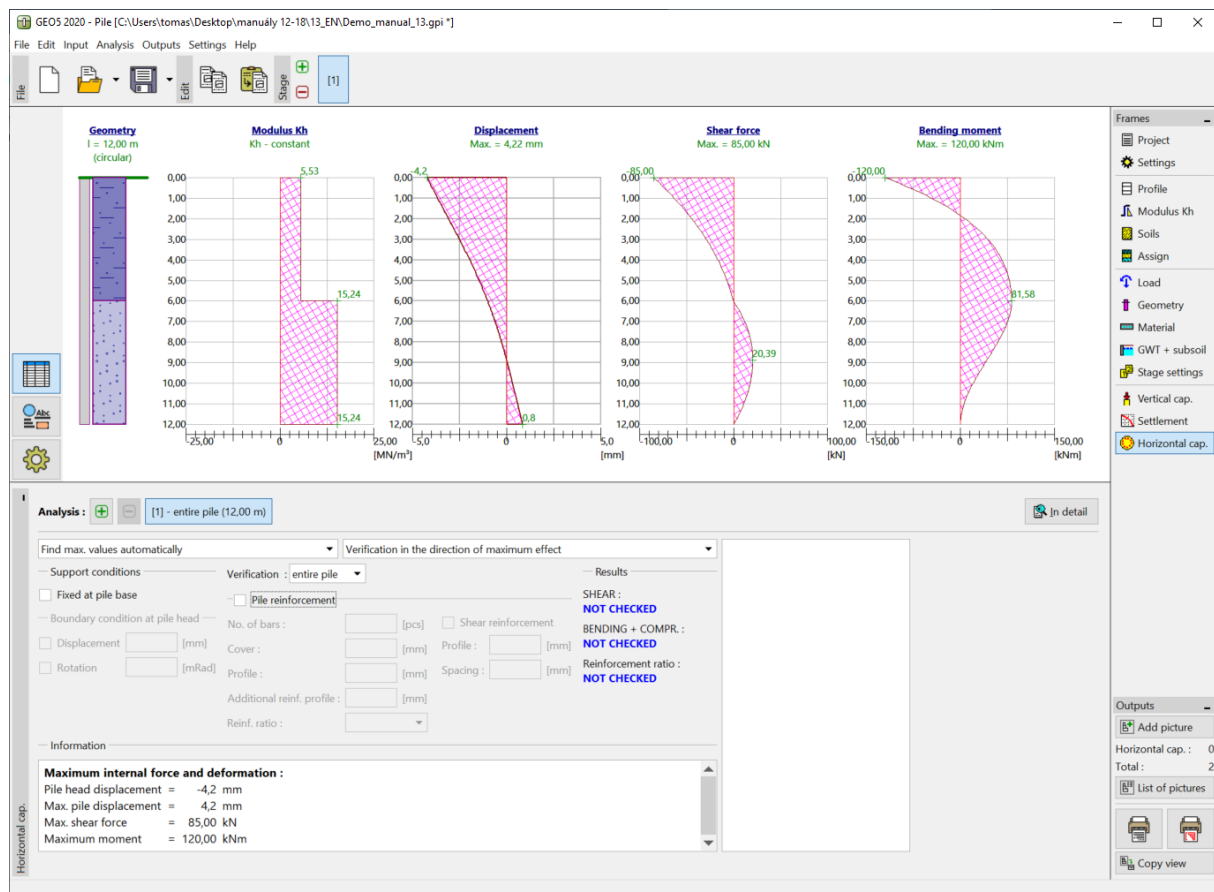

"Modulus k_h" frame

Note: The constant course of the modulus of the 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 the program help – F1).

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

Soil (Soil classification)	Unit weight $\gamma\ [kN/m^3]$	Angle of internal friction $\varphi_{ef}\ [°]$	Angle of dispersion $\beta\ [°]$	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

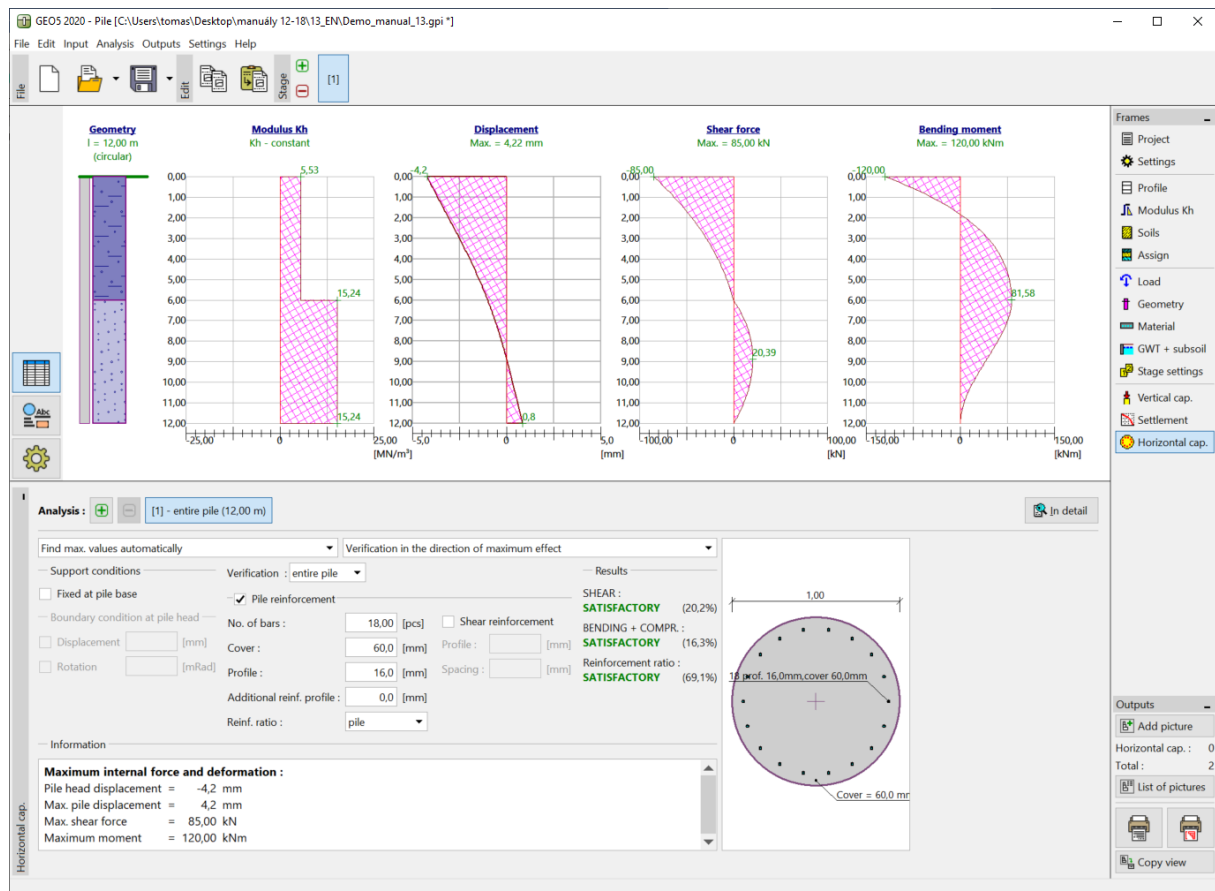*Table with the soil parameters – Horizontal bearing capacity of single pile*

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

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

Note: The boundary condition for a pile fixing at the pile base is modeled first 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 the program help – F1).

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

Horizontal bearing capacity" frame – dimensioning
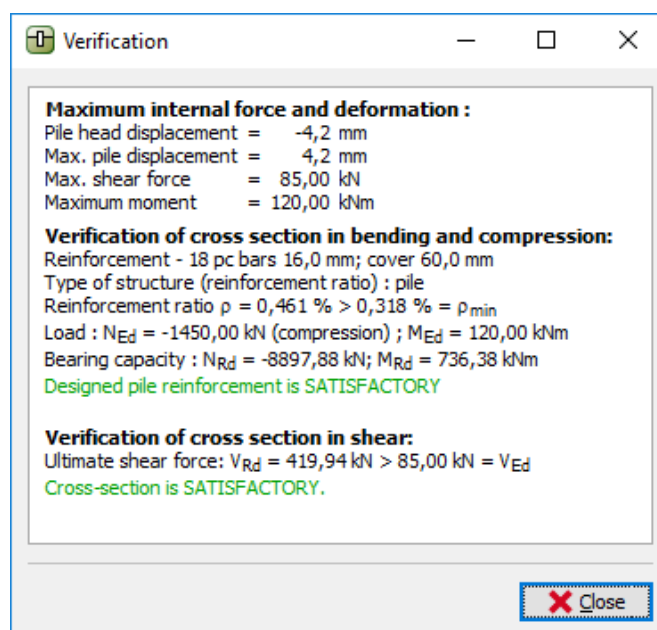
In this case we consider the reinforcement ratio for the laterally loaded single pile in accordance with *CSN EN 1536: Execution of special geotechnical works - Bored piles* (Table 4 – Minimum reinforcement of bored piles). This possibility is set in the program by selecting the reinforcement ratio option "Pile".

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

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

Note: In the case of compressed elements, it is better to use the reinforcement ratio as if it was 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 sectional reinforcement area to the concrete area (for more details, visit the program help – F1).

We can see the use of the bending-subjected pile cross-section and the condition for the minimum reinforcement ratio in the pile dimensioning results (by clicking on the "In detail" button).

Verification — □ ✕

Maximum internal force and deformation :
Pile head displacement =   -4,2 mm
Max. pile displacement =   4,2 mm
Max. shear force   = 85,00 kN
Maximum moment   = 120,00 kNm

Verification of cross section in bending and compression:
Reinforcement - 18 pc bars 16,0 mm; cover 60,0 mm
Type of structure (reinforcement ratio) : pile
Reinforcement ratio ρ = 0,461 % > 0,318 % = ρ_{min}
Load : N_{Ed} = -1450,00 kN (compression) ; M_{Ed} = 120,00 kNm
Bearing capacity : N_{Rd} = -8897,88 kN; M_{Rd} = 736,38 kNm
Designed pile reinforcement is SATISFACTORY

Verification of cross section in shear:
Ultimate shear force: V_{Rd} = 419,94 kN > 85,00 kN = V_{Ed}
Cross-section is SATISFACTORY.

✕ Close

"Verification (detailed)" – Dialogue window

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 a **constant course** of the modulus of the 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 (flexure + pressure): 16,3 %   SATISFACTORY

- RC pile bearing capacity (shear): 20,2 %   SATISFACTORY

- Pile reinforcement ratio: 69,1 %   SATISFACTORY

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

The values and course of the modulus of the horizontal reaction of subsoil k_h will vary depending on the analysis method used and the input soil parameters that affect it. In each calculation method, different soil parameters affect the results, namely:

- CONSTANT: angle of dispersion $\beta\,[-]$,

- *LINEAR (Bowles)*: angle of dispersion $\beta\,[-]$,

  coefficient $k\,\left[MN/m^3\right]$ according to the soil type,

- *According to CSN 73 1004*: whether it is a cohesive or cohesionless soil,

  modulus of horizontal compressibility $n_h\,\left[MN/m^3\right]$,

- *According to VESIC*: modulus of elasticity $E\,[MPa]$.

When the method of calculation of the modulus of the horizontal reaction of the subsoil is changed, we will need to input additional soil parameters into the program (for more information see program help – F1) as follows:

Modulus of subsoil reaction $k_h\,\left[MN/m^3\right]$	Angle of dispersion $\beta\,[-]$	Coefficient $k\,\left[MN/m^3\right]$	Modulus of elasticity $E\,[MPa]$	Modulus of horizontal compressibility $n_h\,\left[MN/m^3\right]$
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 "Modulus Kh" frame and change the settings. We will always change the respective method of calculation of the modulus of the horizontal reaction of subsoil and then add the necessary parameters of soils. We will carry out the procedure for the following methods:

- linear (according to Bowles),

- according to CSN 73 1004,

- according to Vesic.
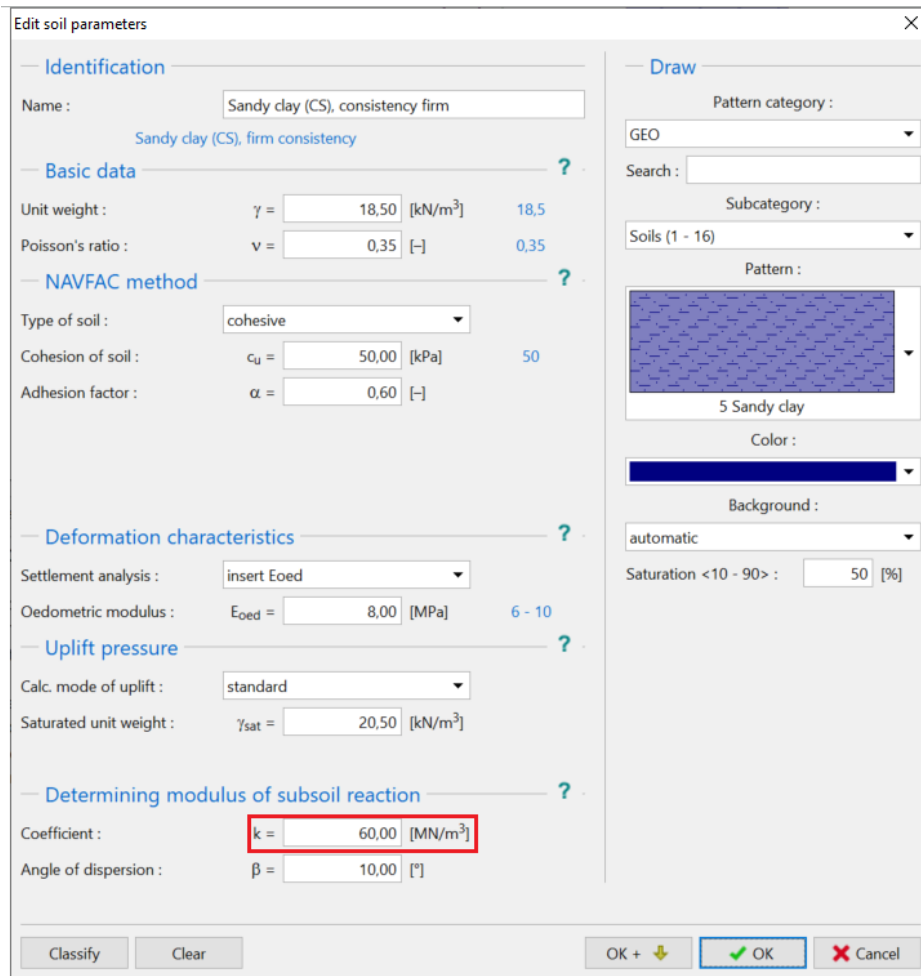
Linear method (according to Bowles)

Firstly, go to the "Modulus Kh" frame and change the settings to "linear".
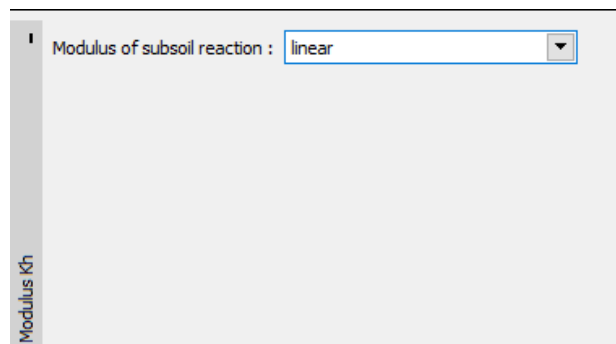
"Modulus Kh" frame

Then, in the "Soils" frame, select the "CS – Sandy clay" soil and click on the "Edit" button. Change the k coefficient to 60 MN/m^3 and click "OK".

"Soils" frame – Edit soil parameters (CS soil)

Repeat the same procedure for soil "S-F – Sand with trace of fines". This time set the k coefficient to 150 MN/m^3.

"Soils" frame – Edit soil parameters (S-F soil)

Now, go to the "Horizontal bearing capacity" frame, where the calculation results can be seen.
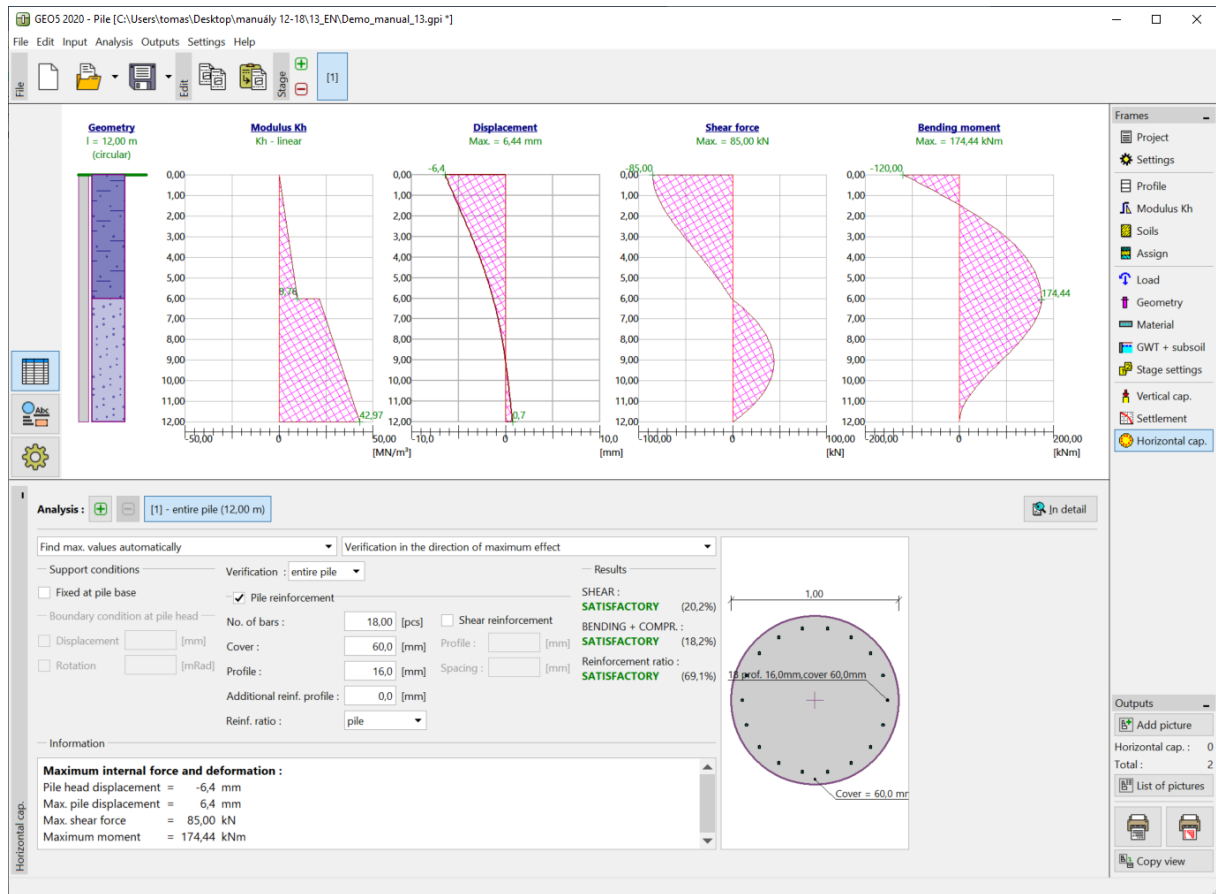
"Horizontal bearing capacity" frame - *Linear course of the modulus of the horizontal reaction of subsoil k_h, deformation and internal forces*
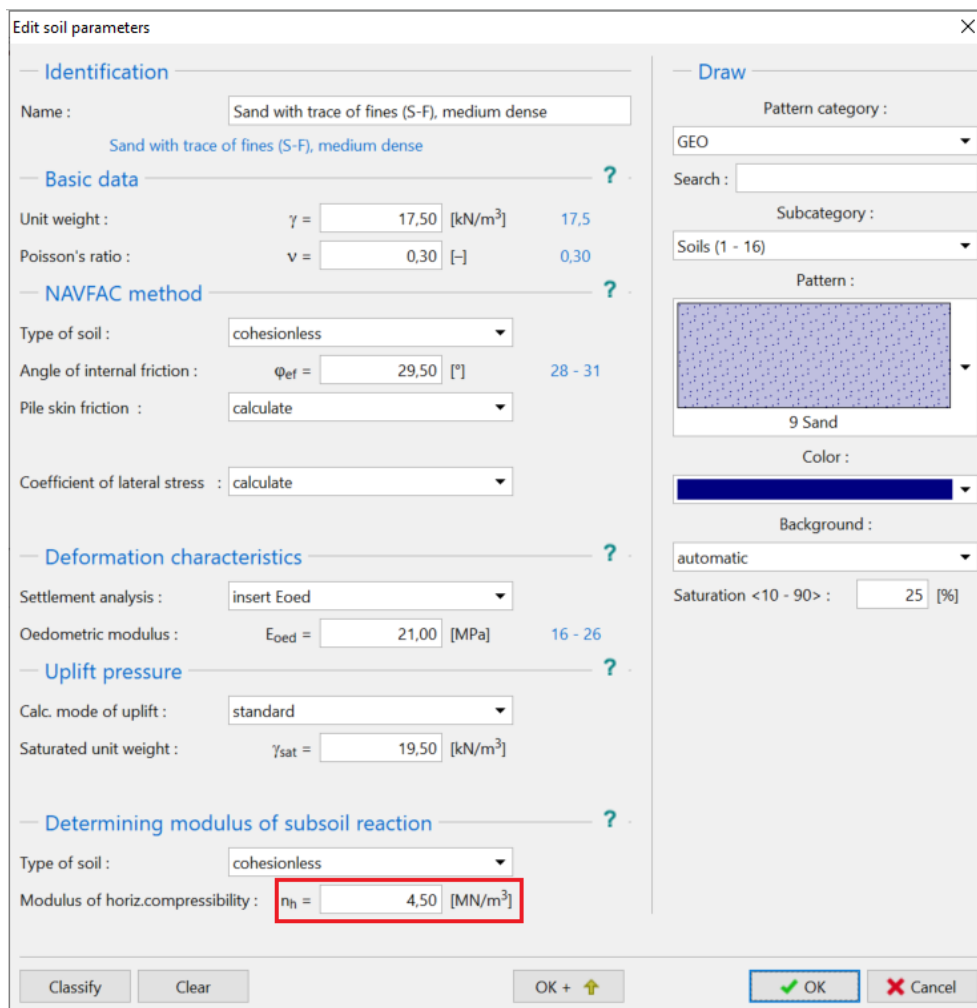
According to CSN 73 1004

Now go to the "Modulus Kh" frame again and change the method to "according to CSN 73 1004".

"Modulus Kh" frame

In the "Soils" frame, it is necessary to set the modulus of horizontal compressibility for the cohesionless "S-F – Sand with trace of fines" soil. Click on the "Edit" button and set the value of the modulus to 4,50 MN/m³.

"Soils" frame – *Edit soil parameters (S-F soil)*

Now the results can be read from the "Horizontal bearing capacity" frame.
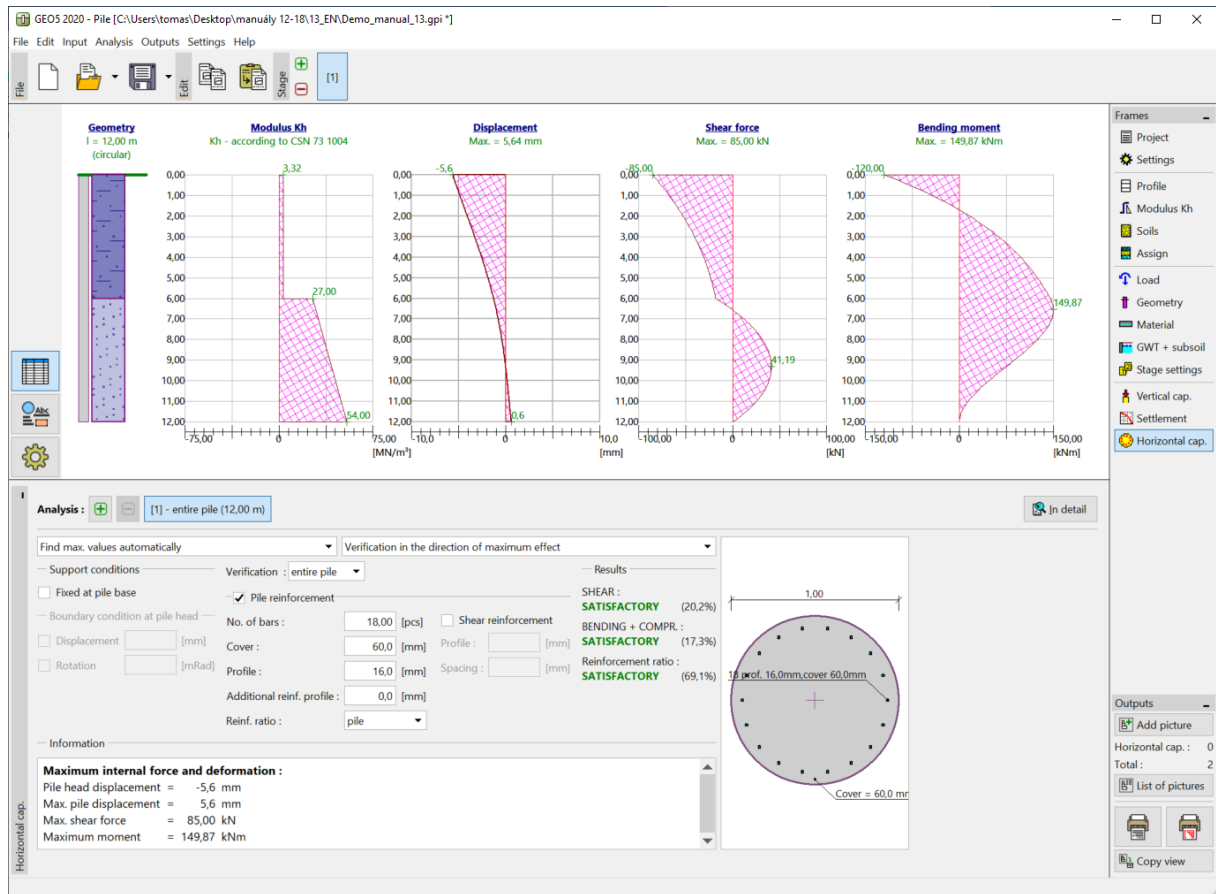
"Horizontal bearing capacity" frame - Course of modulus of subsoil reaction k_h according to CSN

73 1004, deformation and internal forces
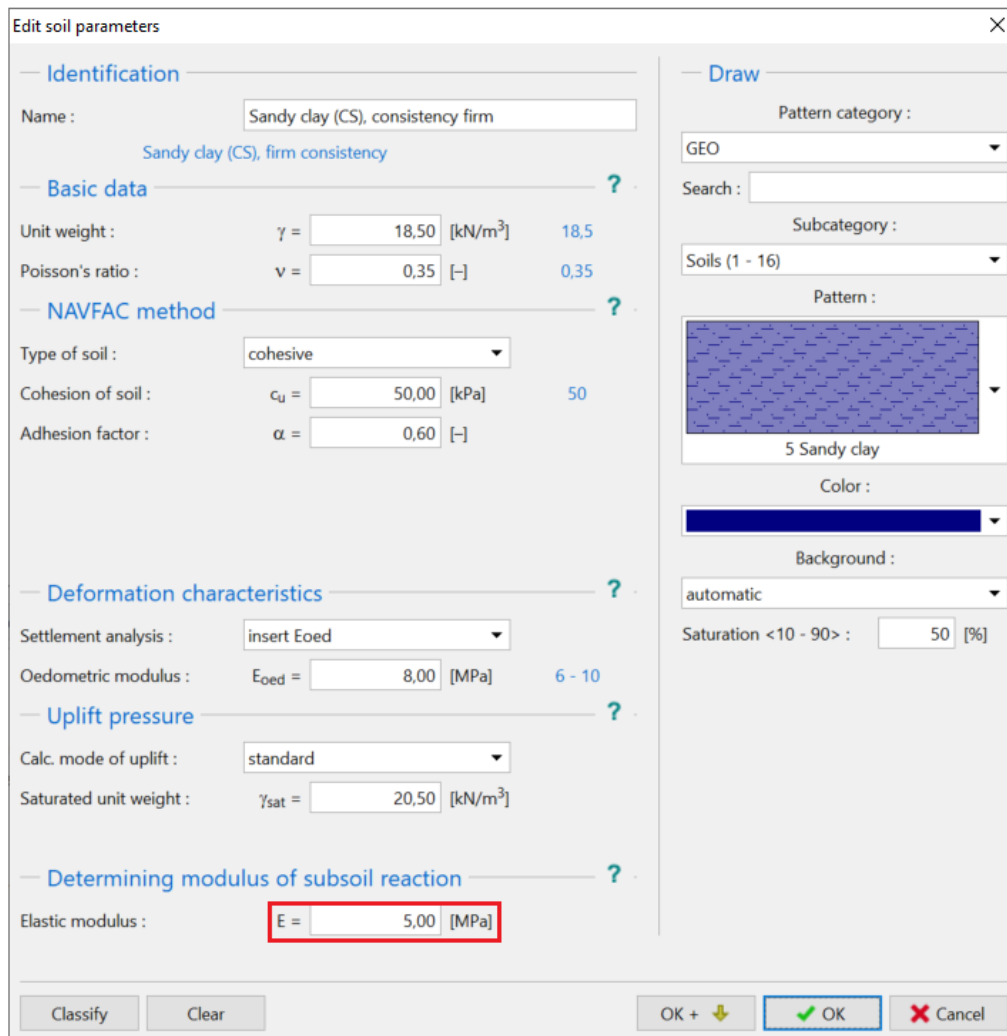
According to Vesic

Once again, go to the "Modulus Kh" frame and change the settings to "according to Vesic".
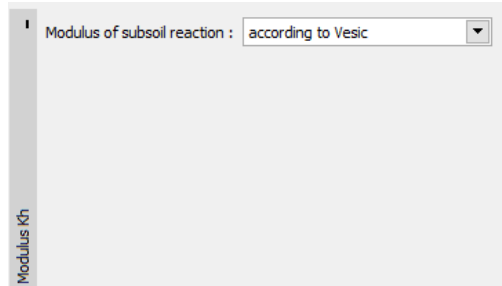
"Modulus Kh" frame

In the "Soils" frame, it is now necessary to set the modulus of elasticity E for both soils. In the case of the "CS – Sandy clay soil", its value will be 5 MPa.

"Soils" frame – Edit soil parameters (CS soil)

Also, set the modulus for the "S-F – Sand with trace of fines" soil. In this case, its value will be 15,50 MPa.

"Soils" frame – Edit soil parameters (S-F soil)

The results can now be seen in the "Horizontal bearing capacity" frame.
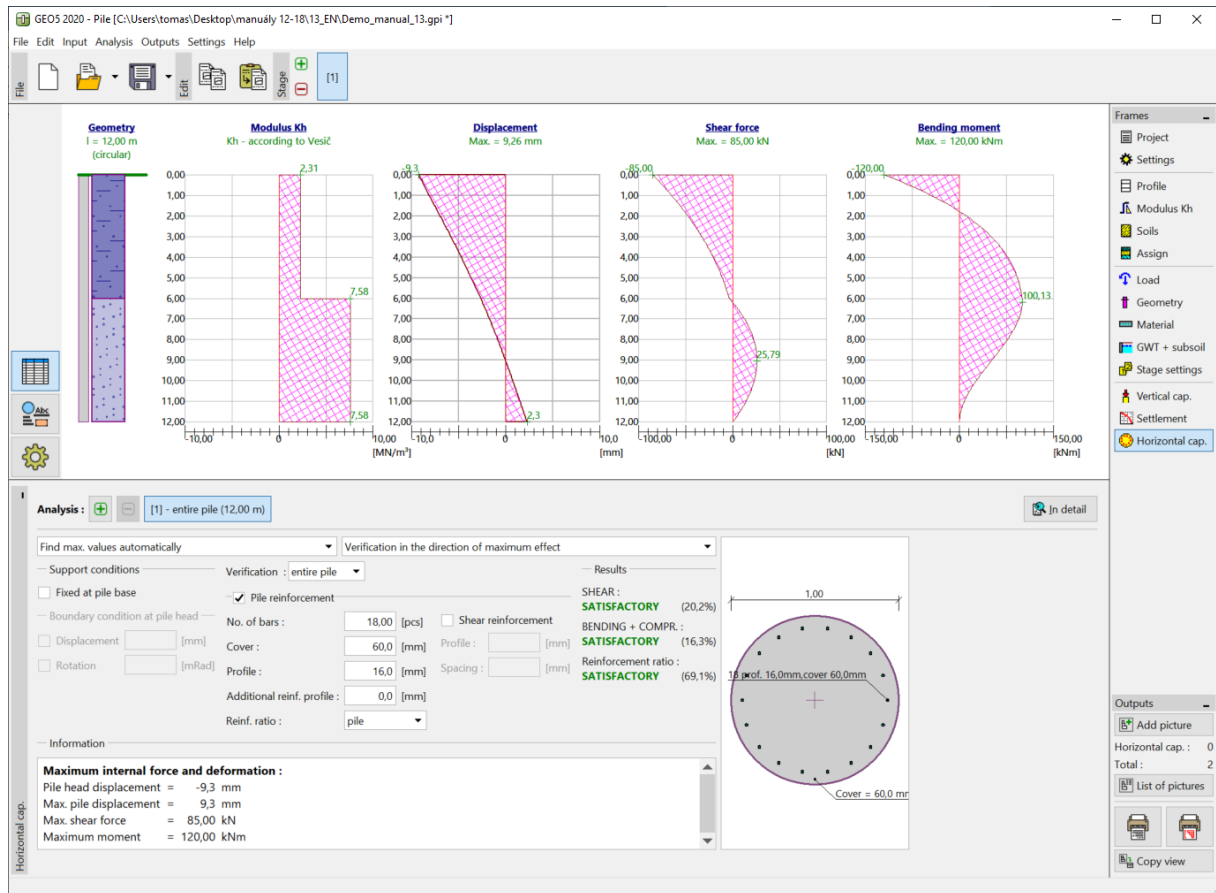
"Horizontal bearing capacity" frame - Course of modulus of horizontal reaction of subsoil k_h

according to Vesic, deformation and internal forces

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

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

Modulus of subsoil reaction $k_h \left[MN/m^3 \right]$	Max. pile displacement $u_{max} \left[mm \right]$	Max. bending moment $M_{max} \left[kNm \right]$	RC pile bearing capacity $\left[\% \right]$
CONSTANT	4.2	120.0	16.3
LINEAR (Bowles)	6.4	174.44	18.2
CSN 73 1004	5.6	149.87	17.3
VESIC	9.3	120.0	16.3

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

Conclusion

From the calculation results, we can see 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.