

### Analysis of a single pile settlement

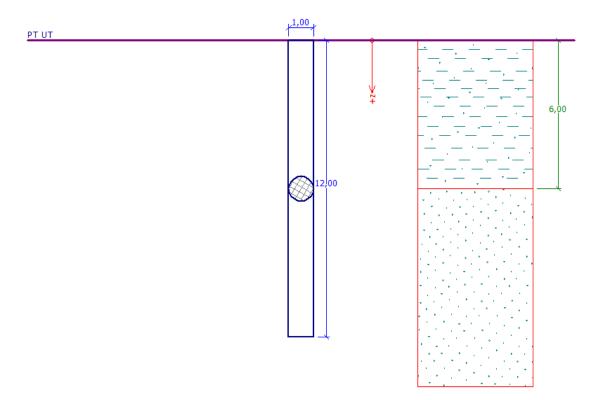
Program: Pile

File: Demo\_manual\_14.gpi

The objective of this engineering manual is to explain the application of the GEO 5 – PILE program for the analysis of the settlement of a single pile in a specified practical problem.

#### **Problem specification**

The general specification of the problem is described in chapter 12. *Pile foundations – Introduction*. All analyses of the single pile settlement shall be carried out on the foundations of the previous problem presented in chapter 13. *Analysis of vertical load-bearing capacity of a single pile*.



Problem specification chart – single pile

#### Solution

We will use the GEO 5 - Piles program to analyze this problem. In the text below, we will describe the solution to this problem 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)

# **GE05**

The **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 of **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 depending on the method applied (NAVFAC DM 7.2, Effective Stress, CSN 73 1002 or Tomlinson).

The **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, therefore, even be used to determine the vertical bearing capacity of a single pile when the capacity corresponds to the allowable settlement (usually 25 mm).

#### Specification process: Linear settlement theory (POULOS)

In the "Pile" program, open up the file from manual no. 13. In the "Settings" frame, we will leave the analysis settings unchanged – we will use the "Standard – EN 1997 – DA2" setting, which is the same as in the previous problem. The analysis of bearing capacity will be done according to NAVFAC DM 7.2. We will also check the box "Do not calculate horizontal bearing capacity". The linear loading curve (Poulos) has already been specified for this analysis setting.

'	Analysis settings :	(input for current task)		Select settings	- Analysis method Analysis of vertical bearing capacity :	analytical solution
	Coefficients EN 19 Steel structures : Partial factor on be	Concrete structures : Coefficients EN 1992-1-1 : Steel structures : Partial factor on bearing capacity of steel cross section : Timber structures : Partial factor for timber property : Modif. factor of load duration and moisture content : Coeff. of effective width for shear stress :		Settings administrator	, , ,	analysis for drained conditions
	Partial factor for ti Modif. factor of loa			di administrator	Do not calculate horizontal bearing of the second secon	apacity
5	Load settlement cu Horizontal bearing Verification method	capacity : Elastic subsoil (p-y met lology : according to EN 1997				
Settings	Design approach :	2 - reduction of action	s and resistances	🗲 Edit		

#### "Settings" frame

Note: The analysis of the limit loading curve is based on the theory of elasticity. The ground is characterized by the modulus of deformation  $E_{def}$  and Poisson's ratio v.

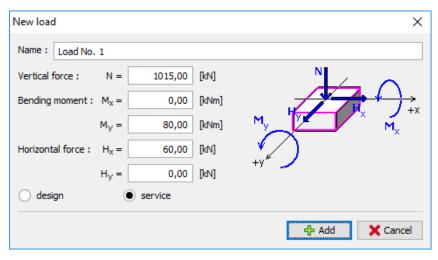
In the next step, we will go to the "Soils" frame and check the deformational properties of soils required for the analysis of settlement, i.e., the oedometric modulus  $E_{oed}$ , or deformation modulus  $E_{def}$  and Poisson's ratio v.

# **GE05**

Soil (Soil classification)	Unit weight $\gamma \left[ kN/m^3 \right]$	friction	Cohesion of soil $c_{ef} / c_u [kPa]$	Poisson´s ratio v [–]	Oedometric modulus $E_{oed} = [MPa]$
CS – Sandy clay, firm consistency	18,5	-/0,0	-/50,0	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 a single pile

Then, in the "Load" frame, we will define the service load for the purpose of analyzing the settlement of a single pile. Click on the "Add" button and add a new load with the parameters as shown in the figure below.



"New load" Dialog window

All other frames will remain unchanged. We can now continue to the settlement analysis in the "Settlement" frame.

In the "Settlement" frame, we will specify the secant modulus of deformation  $E_s$  [*MPa*] for each of the soil types using the "edit  $E_s$ " button.

For the 1<sup>st</sup> layer of *cohesive soil* (class CS), we will set the value of the secant modulus of deformation to  $E_s \cong 17.0 \ MPa$ . For the 2<sup>nd</sup> layer of *cohesionless soil* (class S-F), we will assume the secant modulus of deformation  $E_s \cong 24.0 \ MPa$ .

### **GEO5**

Input for load settlement curve X				
Input of parameters of the lay Assigned soil : Layer beg. (from FG) : Layer end (from FG) : - Parameters	yer No. : 1 Sandy day (CS), consistency firm 0,00m 6,00m, layer thickness : 6,00m - Help			
E <sub>s</sub> = <u>17,00</u> [MPa]	Secant modulus of deformation $E_s$ [MPa]: <b>Rocks:</b> Class R3 105,50 Class R4 57,30 Class R5 41,00 Class R6 23,90 <b>Non-cohesive soils:</b> (Id = relative compaction) Id = 0.5 18,40 Id = 0.7 25,00 Id = 1.0 47,80 <b>Cohesive soils:</b> (Ic = consistency index) Ic = 0.5 12,50 Ic > 1 23,90			
	OK + ∱ OK + 🖖 🗸 OK	X Cancel		

"Input for load settlement curve – secant modulus of deformation  $E_{\rm s}$  " Dialog window – CS soil

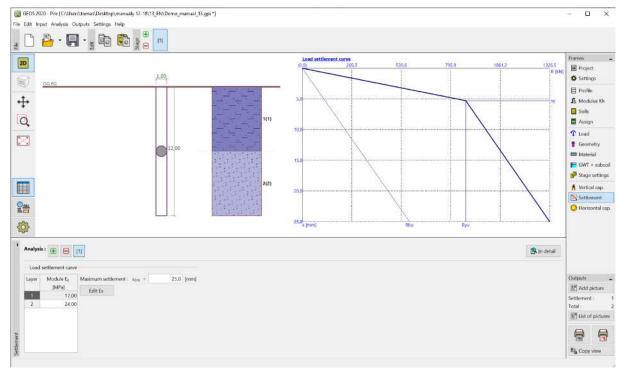
Input for load settlement curve		×
Input of parameters of the layer No Assigned soil : Layer beg. (from FG) : Layer end (from FG) : – Parameters $E_s = 24,00$ [MPa]	.: 2 Sand with trace of fines (S-F), medium dense 6,00m 12,00m, layer thickness : $6,00m$ - Help Secant modulus of deformation E <sub>s</sub> [MPa]: <b>Rocks:</b> Class R3 158,00 Class R4 106,66 Class R5 77,52 Class R6 47,72 <b>Non-cohesive soils:</b> (Id = relative compaction) Id = 0.5 28,40 Id = 0.7 44,74 Id = 1.0 88,54 <b>Cohesive soils:</b> (Ic = consistency index) Ic = 0.5 20,22 Ic > 1 48,12	
	OK + ∱ OK + ⊕ ✔ OK	X Cancel

"Input for load settlement curve – secant modulus of deformation  $\,E_s\,$ " Dialog window – S-F soil



Note: The secant modulus of deformation  $E_s$  depends on the diameter of the pile and the thickness of each of the 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.

Further, we will set the limit settlement, which is the maximum settlement value for which the loading curve is calculated. In this task, we will consider a maximum settlement of 25 mm.



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

Then, we will click on the "In detail" button and in the dialog window, we can see the settlement value calculated for the maximum service load.

🕀 Verification	-	-		×
Analysis of load settlement curve Load at the onset of mobilization of skin The settlement for the force R <sub>yu</sub> Total resistance Maximum settlement	friction R <sub>yu</sub> s <sub>y</sub> R <sub>c</sub> s <sub>lim</sub>	= = 13 =	5,2 mm 326,49 kN 25,0 mm	n
The settlement for maximum service loa	d V = 1015,0	OKN i	s 11,3mm.	
			XQ	ose

Results of settlement

# **GE05**

For the vertical bearing capacity analysis using the **NAVFAC DM 7.2**, the resultant settlement of the single pile is **11,3 mm**.

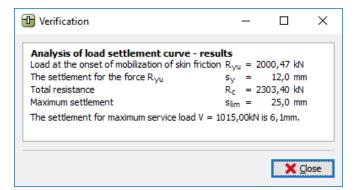
Single pile settlement analysis: Linear settlement theory (POULOS), other methods

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

Edit current settings : Pile					×
Materials and standards Pile					
Analysis for drained conditions :	Effective stress		•		
Analysis for undrained conditions :	Tomlinson		▼		
Load settlement curve :	linear (Poulos)		•		
Horizontal bearing capacity :	Elastic subsoil (p-y m	ethod)	-		
Verification methodology :	according to EN 1997	7	-		
Design approach :	2 - reduction of actio	ns and resistances	<b>•</b>		
Democrat desire situation Trans	tent destas attas ten	A set download all store with setting	Coloria de las situations	1	
Permanent design situation Trans	ient design situation	Accidental design situation	Seismic design situation		
- Partial factors on actions (A)		favourable Favo	ourable		
Permanent actions :	γ <sub>G</sub> =	1,35 [-]	1,00 [-]		
- Partial factors for resistances (R)					
Bored piles Driven piles CFA pi	les				
Partial factor on shaft resistance :	γ <sub>s</sub> =	1,10 [-]			
Partial factor on base resistance :	γь =	1,10 [-]			
Partial factor on resistance in tens	sion: γ <sub>st</sub> =	1,15 [-]			
					🗸 ОК
					🗙 Cancel

"Edit current settings" Dialog window

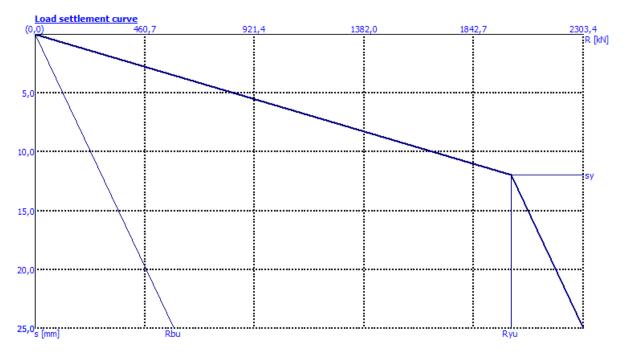
Subsequently, we will get back to the "Settlement" frame, where we will see the results. The magnitude of the limit settlement  $s_{\rm lim}$ , the pile type, and the secant modulus of deformation  $E_s$  remain identical with those used in the previous analysis.



*"In detail" Dialog window – effective stress method results* 

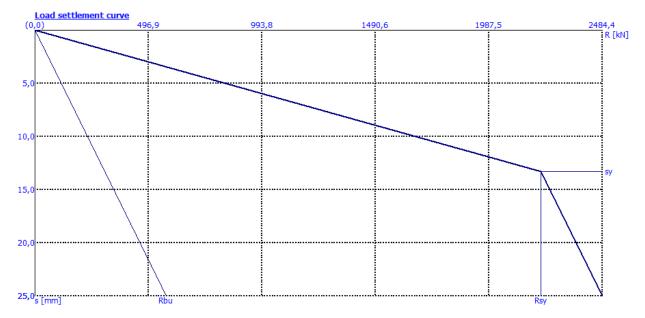


For the vertical bearing capacity of a single pile determined using the *EFFECTIVE STRESS* method, the resultant settlement is s = 6.1 mm.



"Settlement" frame - Linear loading curve (according to Poulos) for the Effective Stress method

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



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



The results of the single pile settlement analysis according to linear theory (*Poulos*) dependent 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	2303,4	6,1
CSN 73 1002	2215,89	2484,40	6,1

Summary of results – Settlement of a single pile according to Poulos

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

This solution is independent of the previous analyses of the vertical bearing capacity of a pile. The method is based on the solution to regression curve equations according to the results of static pile loading tests. This method is mostly used in Czechia and Slovakia. It provides reliable and conservative results for the local engineering geological conditions.

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

Edit current settings : Pile	X
Materials and standards Pile	
Analysis for drained conditions : CSN 73 1002	
Analysis for undrained conditions : Tomlinson	
Load settlement curve : nonlinear (Masopust)	
Horizontal bearing capacity : Elastic subsoil (p-y method)	
Verification methodology : according to EN 1997	
Design approach : 2 - reduction of actions and resistances	
Permanent design situation Transient design situation Accidental design situation Seismic design situation	-
Partial factors on actions (A) Unfavourable Favourable	
Permanent actions : $\gamma_{G} = 1,35$ [-] 1,00 [-]	
Partial factors for resistances (R)	
Bored piles Driven piles CFA piles	
Partial factor on shaft resistance : $\gamma_s = 1,10$ [-]	
Partial factor on base resistance : $\gamma_b = 1,10$ [-]	
Partial factor on resistance in tension : $\gamma_{st} = 1,15$ [-]	
	🗸 ОК
	X Cancel

"Edit current settings" Dialog window



The other data remain unchanged. Then we will continue to the "Settlement" frame.

We consider the *service load* for the nonlinear limit loading curve because this is an analysis according to the limit state of serviceability. We will leave the shaft protection factor value at  $m_2 = 1.0$ . That means 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  $s_{\rm lim}$  and secant modulus of deformation  $E_s$  identical with those used in the previous analyses.

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

Input for load settlement curve X				
Input of parameters of the Assigned soil : Layer beg. (from FG) : Layer end (from FG) : — Parameters ————————————————————————————————————	layer No. : 1 Sandy clay (CS), consistency firm 0,00m 6,00m, layer thickness : 6,00m			
a = 46,00 [-] b = 20,00 [-]	Regression coefficients input a,b [-]:     Rocks     Good rock   246 225     Fair rock   169 139     Poor rock   131 94     Very poor rock   97 108     Non-cohesive soils   (Id = relative compaction)     a   b     Id = 0.5   62 16     Id = 0.7   91 48     Id = 1.0   154 115     Cohesive soils     {Ic = consistency index}     a   b     Ic = 0.5   46 20     Ic > 1   97 108			
	OK + ∱ OK + ♣ ✔ OK	X Cancel		

"Input for load settlement curve – regression coefficients a, b (e, f)" Dialog window – CS soil

## **GEO5**

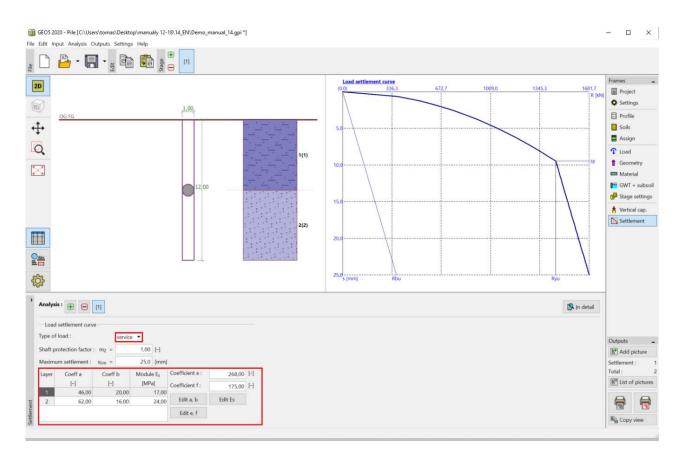
Input for load settlement curve		×	
Input of parameters of the layer Assigned soil : Layer beg. (from FG) : Layer end (from FG) : — Parameters ————	No.: 2 Sand with trace of fines (S-F), medium dense 6,00m 12,00m, layer thickness : 6,00m Help		
a = 62,00 [-] b = 16,00 [-]	Regression coefficients input a,b [-]:     Rocks     Good rock		
	OK + ∱ OK + ⊕	X Cancel	

"Input for load settlement curve – regression coefficients a, b" Dialog window – S-F soil

Input for load settlement	curve	$\times$
Input of parameters belov Layer beg. (from FG) : Layer end (from FG) :	v pile base 12,00m -	
- Parameters	- Help	
e = 268,00 [-]	Regression coefficients input e,f [-]:	
f = 175,00 [-]	e   f     Good rock	
	VOK X Canc	el

"Input for load settlement curve – regression coefficients e, f" Dialog window

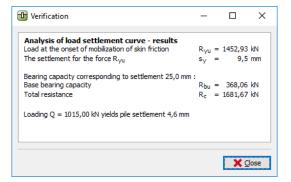




"Settlement" frame – solution according to the nonlinear settlement theory (Masopust)

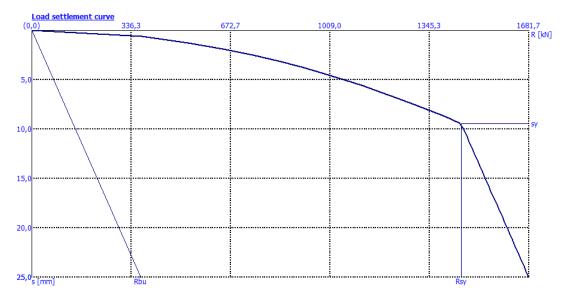
Note: The specific skin friction depends on regression coefficients "a, b". The stress on the pile base (at fully mobilized skin friction) depends on regression coefficients "e, f". The values of these regression coefficients were derived from regression curve equations determined on the basis of a statistical analysis with results from about 350 static pile loading tests in Czechia and Slovakia (for more details visit the program 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 the program help – F1).

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



Results of settlement - nonlinear curve





"Settlement" frame - Nonlinear loading curve (according to Masopust)

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

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

#### Conclusion

The program calculated the pile settlement for the specified service load to be within the range from 4,6 to 11,3 mm (depending on the method used). This settlement is smaller than the maximum allowable settlement – the pile is satisfactory from the 2<sup>nd</sup> limit state point of view.