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Master Thesis

Elaboration and implementation of the algorithm to design deep foundations in form of foundations piles

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Authors' contribution of particular parts of the Master Thesis

Jakub Majchrzak

- Designing a part of the user interface responsible for displaying errors and results of calculations
- Development of algorithms for testing the strength of foundation piles, negative friction and displacements
- Chapter 2. Elaboration of algorithms
- Chapter 4. Example calculations

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- Designing a part of the user interface responsible for entering user data, displaying the element view
- Development of algorithms for testing the strength of piles, cap reinforcement and for calculating the stresses created in the soil
- Chapter 1. Introduction
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Abstract

Foundation piles are more and more used in difficult soils conditions but they are still very incomprehensible for many engineers. That is the reason why they reach for the automated solutions. Unfortunately, the choice of software used to calculate piles is very limited and most of them are either not viable or unintuitive for the first-time users. The thesis presents the algorithms, which automate whole process of calculations. Next, the implementation of algorithms in Python programming language is described, followed by installation and user's manual. The next part compares the results of calculations from the program and from the literature. The result of this diploma thesis is the Soldis PROJEKTANT software module, which allows the user to design foundation piles in an easy and quick way.

Basic markings

Capital Latin letters:

A_b - base area under pile

A_c - cross section area of concrete in single pile

A_f, B_f - partial factor to calculation rotation at the level of the calculated ceiling level of load-bearing soil

A_{pH}, B_{pM} - partial factor to calculation lateral pressure on the ground

A_s - cross sectional area of reinforcement in single pile

$A_{s,i}$ - pile shaft surface area in layer *i*

A_M, B_M - partial factor to calculation bending moment of the pile

A_y, B_y - partial factor to calculation displacement at the level of the calculated ceiling level of load-bearing soil

B - width of the approximated pile shape

B_f - width of the foundation slab

B_G - width of the virtual foundation slab

B_s - width of the foundation stem

D - diameter of the pile

D_f - ordinate of foundation slab

D_p - design diameter of the pile

E_s - design value of modulus of elasticity of reinforcing steel

E_{cm} - secant modulus of elasticity of concrete

$F_{c,d}$ - design value of axial load

$F_k{}'$ - effective characteristic value of total concentrated load

$H_{L,G,c}$ - stable characteristic horizontal force

$H_{L,G,d}$ - stable design horizontal force

$H_{L,Q,c}$ - variable characteristic horizontal force

$H_{L,Q,d}$ - variable design horizontal force

$H_{all,d}$ - whole design horizontal force

H_f - height of the foundation slab

H_s - height of the foundation stem

$H_{1,k}$ - horizontal force for one pile

I_D - degree of compaction

I_L - degree of plasticity

J - modulus of pile

K - partial factor taking into account the number of piles in a row parallel to bending direction

K_c, K_q - partial factor to calculation of lateral pressure on the ground

L - length of the pile

L_f - length of the foundation slab

L_G - length of the virtual foundation slab

L_s - length of the foundation stem

$M_{L,G,c}$ - stable characteristic bending moment

$M_{L,G,d}$ - stable design bending moment

$M_{L,Q,c}$ - characteristic design bending moment

$M_{L,Q,d}$ - variable design bending moment

$M_{all,d}$ - variable design bending moment

$M_{z,d}$ - design value of bending moment of the pile

$M_{0,k}$ - characteristic value of the edometric modulus of primary compressibility

$M_{1,k}$ - bending moment force for one pile

N - number of piles in group

R - distance between pile and stress zone

$R_{b,k}$ - characteristic value of the base resistance of a pile

$R_{b,d}$ - design value of the base resistance of a pile

$R_{c,d}$ - design load capacity

$R_{s,k}$ - characteristic value of the shaft resistance of a pile

$R_{s,d}$ - design value of the shaft resistance of a pile

$R_{s,d,cal}$ - design value of the shaft resistance of a pile with taking into account design value of negative friction

$R_{c,d,cal}$ - design load capacity with taking into account design value of negative friction

$R_{c,d,GP}$ - design load capacity with taking into account design value of negative friction of group of piles

S_p - technological factor by content of PN-83 / B-02482

S_n - technological factor to calculation of lateral pressure on the ground

$S_{s,i}$ - technological factor by content of PN-83 / B-02482 for layer *i*

Tn_c - characteristic value of negative friction

Tn_d - design value of negative friction

$Q_{Tn,c}$ - characteristic value of weight layers with negative friction

$V_{all,d}$ - whole design vertical force

$V_{G,c}$ - - stable characteristic vertical force

$V_{G,d}$ - - stable design vertical force

$V_{Q,c}$ - - variable characteristic vertical force

$V_{Q,d}$ - - variable design vertical force

$V_{pile,c}$ - characteristic value of pile weight

$V_{stem,c}$ - characteristic value of pile stem

$V_{slab,c}$ - characteristic value of foundation slab

Small Latin letters:

b - overall width of a cross-section

c - cohesion intercept

d - effective depth of a cross-section

e - eccentricity

f_{cd} - design value of concrete compressive strength after 28 days

f_{ck} - characteristic value of concrete compressive strength after 28 days

f_k' - effective value of the load in the level of the pile foundation

f_y - yield strength of reinforcement

f_{yd} - design yield strength of reinforcement

f_{yk} - characteristic yield strength of reinforcement

h - overall depth of a cross-section

h_i - height of the soil layer

h_s - height of the foundation stem

h_w - design ceiling level of load bearing layer

h_z - ceiling of load-bearing soil layer

h' - reduced height of the pile

m - partial factor of deformability of the soil

m_1 - reduction factor including overlap of stress zones around singular piles

$q^{(n)}$ - characteristic load capacity of base of pile by content of PN-83 / B-02482 *i*

$q_{b,k}$ - characteristic value of the unitary resistance of the pile base

$q_{s,i,k}$ - characteristic value of the unitary resistance of the pile side in layer *i*

$p_{z,d}$ - design value of lateral pressure on the ground

r - distance between piles

r_{kr} - distance between side pal and edge of foundation slab

$r_{z,c}$ - characteristic value of load bearing capacity of lateral pressure on the ground

$r_{z,d}$ - design value of load bearing capacity of lateral pressure on the ground

s_{sr} - medium foundation settlement

$t_i^{(n)}$ - characteristic load capacity of soil alongside of pile by content of PN-83 / B-02482 for layer *i*

x - neutral axis depth

y - horizontal displacement of the head of pile

y_{kon} - horizontal displacement of the whole construction

$y_{kon,max}$ - maximum horizontal displacement of the whole construction

y_0 - horizontal displacement at the level of the calculated ceiling level of load-bearing soil

$y_{0,max}$ - maximum horizontal displacement at the level of the calculated ceiling level of load-bearing soil

z - ordinate of foundation pile

z_{olbs} - real ordinate of load bearing soil

$z_{clbs,V}$ - computational ordinate of load bearing soil due to vertical stresses

$z_{clbs,H}$ - computational ordinate of load bearing soil due to horizontal stresses

Small Greek letters:

α - partial factor of deformability of pile

α_i - value of the angle of the stress zone

β - correction factor to calculation of lateral pressure on the ground

φ - angle of internal friction of the ground

φ_0 - angle of rotation at the level of the calculated ceiling level of load-bearing soil

$\varphi_{0,max}$ - maximum angle of rotation at the level of the calculated ceiling level of load-bearing soil

γ_b - partial factor of pile basis to load bearing capacity

γ_s - partial factor of pile side to load bearing capacity

γ_G - partial factor to dead and unfavorable loads

γ_Q - partial factor to live and unfavorable loads

γ_M - partial factor to properties of soil

γ_b - partial factor to load bearing capacity of base of pile

γ_s - partial factor to load bearing capacity of side of pile

ε_c - compressive strain in the concrete

ε_{cu} - ultimate compressive strain in the concrete

ε_{yd} - strain of reinforcement or prestressing steel at maximum load

η - correction factor for axial stress strength of concrete cross section

η_s - factor distribution of stresses in the ground

σ_{s1} - Axial stress in the tensed reinforcement bars

σ_{s2} - Axial stress in the compressed reinforcement bars

$\sigma'_{v,0,z,k}$ - Primary effective geostatic stress

$\sigma'_{v,d,z,k}$ - Additional effective geostatic vertical stress

λ - slenderness ratio

1. Introduction

1.1. Short description of foundation piles

Foundation piles are currently used for setting up a lot of different building object. The main reason to use this type of foundations is layer or layers of weak load-bearing soils. The second significant cause is necessity to carry very large loads on a small surface.

The pile is an elongated element which carry forces on the pile base and peripheral. The stem consists of head, side and foot (basis). At the top of head is located concrete slab, which distributes forces from construction the group of piles. Foundations are usually made from concrete of class C30/37 or higher (due to exposure classes).

Foundation piles can be divided to:

- driven piles – which are driven or vibrated to the soil
- bored piles – where at the beginning soil is removed and tha the pile is made

In the master thesis the calculation approach and all coefficients are for example of bored, pushed pile in protective tube.

1.2. The aim and goal of thesis

The aim of this work is to create and implement rules checking the strength of foundation piles in various ground conditions in program Soldis PROJEKTANT.

The scope of work includes:

- algorithmization of dimensioning procedures based on the Eurocode PN-EN 1997-1 and PN-B-02482
- implementation of dimensioning rules in a Python environment
- creating an interface and adding rules in the program environment Soldis PROJEKTANT

2. Elaboration of algorithms

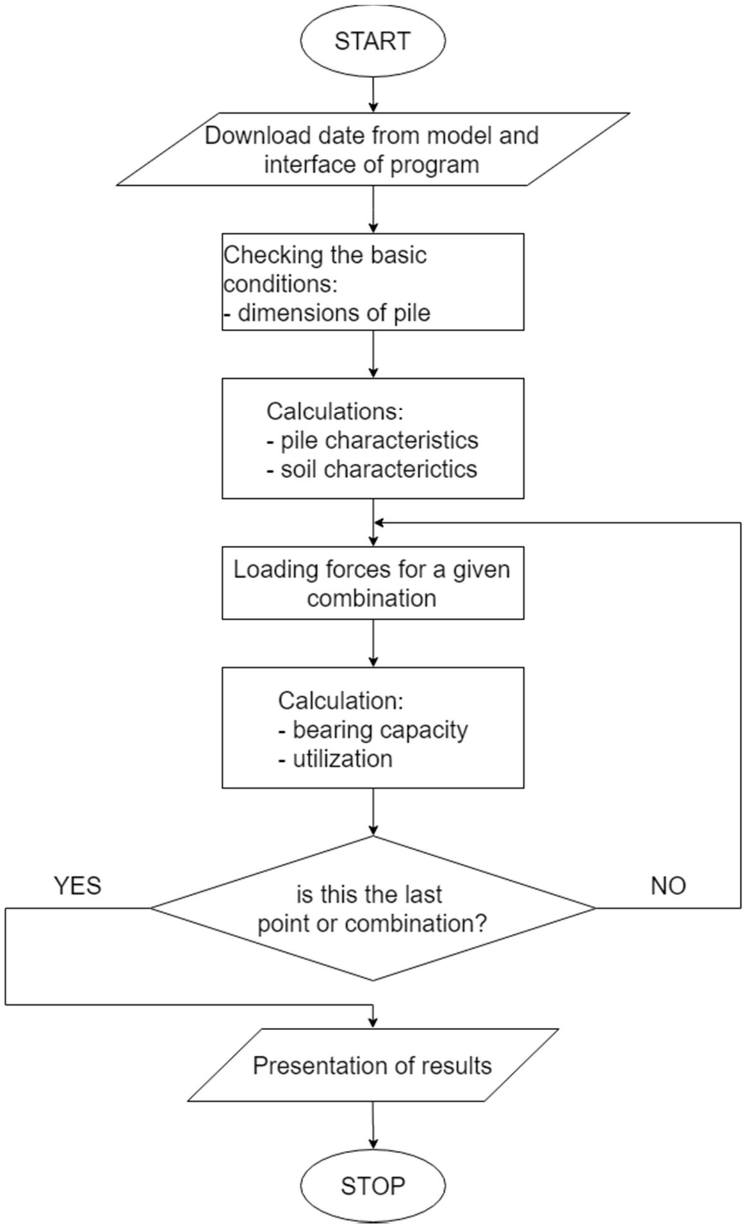
In Eurocode 7 [N3] point 1.4 (5) is written: “It is permissible to use alternatives to the Application Rules given in this standard, proceeded it is shown that the alternative rules accord with the relevant Principles and are at least equivalent with regard to the structural safety, serviceability and durability, which would be expected when using Eurocodes.” One of the proven alternatives is older Polish Standard PN-B-02482 [N1] which was previously used for the safe design of piles, and this Standard is mainly used in dimensional tool cooperating with the program SOLDIS Projektant.

The calculation of foundation piles is a complex issue in itself, mainly due to the appropriate modeling of the interactions between soil layers and the foundation. Also just describing the properties of the soil through coefficients that are often read from charts or different computational approaches allowed by the Eurocode entries result in different design practices that are available in the literature on the subject.

In professional practice, calculations are mainly performed by companies associated with the construction of foundation piles. Possibilities for collecting experience and data from objects created by them, create conditions for optimal design and proposing solutions for given, often complex soil conditions.

2.1. The overall algorithm of the program

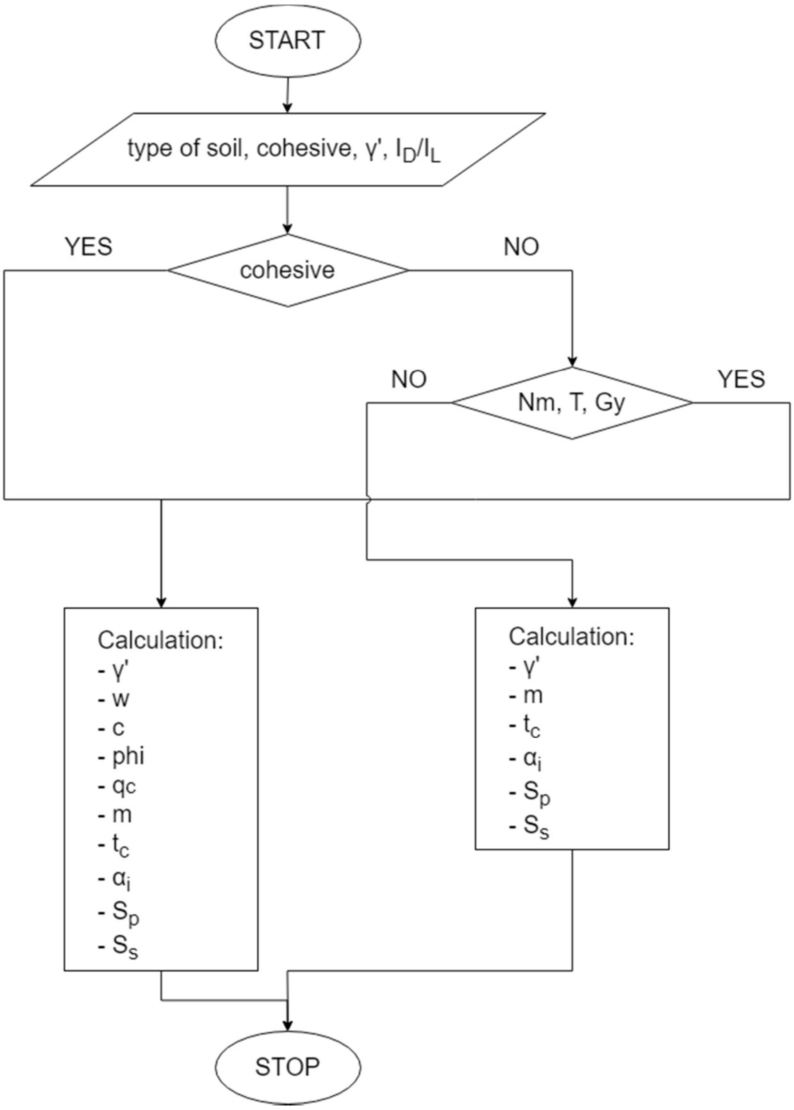
The following algorithm shows the scheme of the program. Calculation and checking of the standard conditions are done for each load combination. At the end, the maximum pile effort is presented for each calculation case.



Algorithm 1 general algorithm of the program's work

2.2. Soil parameters

To the calculation of load bearing capacity of piles is needed to obtain additional parameters of soil layers and technological coefficients.



Algorithm 2 Calculation of additional parameters of soil

2.3. Calculation of external forces

All partial factors are performed for calculation procedure 2* and calculation approach 2 – A1 "+" M1 "+" R2 according to the polish appendix of [N3].

Stable vertical force:

$$V_{G,d} = \gamma_G \cdot (V_{G,c} + N \cdot V_{pile,c} + V_{slab,c} + V_{stem,c} + V_{soil,c})$$

Variable vertical force:

$$V_{Q,d} = \gamma_Q \cdot V_{Q,c}$$

Whole vertical force:

$$V_{all,d} = V_{G,d} + V_{Q,d}$$

Stable horizontal force:

$$H_{L,G,d} = \gamma_G \cdot H_{L,G,c}$$

Variable horizontal force:

$$H_{Q,G,d} = \gamma_Q \cdot H_{L,Q,c}$$

Whole horizontal force:

$$H_{all,d} = H_{L,G,d} + H_{Q,G,d}$$

Stable bending moment:

$$M_{L,G,d} = \gamma_G \cdot M_{L,G,c}$$

Variable bending moment:

$$M_{L,Q,d} = \gamma_Q \cdot M_{L,Q,c}$$

Whole bending moment:

$$M_{all,d} = M_{L,G,d} + M_{L,Q,d} + D_f \cdot H_{all,d}$$

2.4. Design load capacity of pushed pile

Design value of the base resistance of a pile:

$$R_{b,d} = A_b \cdot q_{b,k} / \gamma_b$$ *(PN-EN 1997-1, equation 7.9)*

Design value of the shaft resistance of a pile:

$$R_{s,d} = \sum_{i=1}^{n} A_{s,i} \cdot q_{s,i,k} / \gamma_s$$ *(PN-EN 1997-1, equation 7.9)*

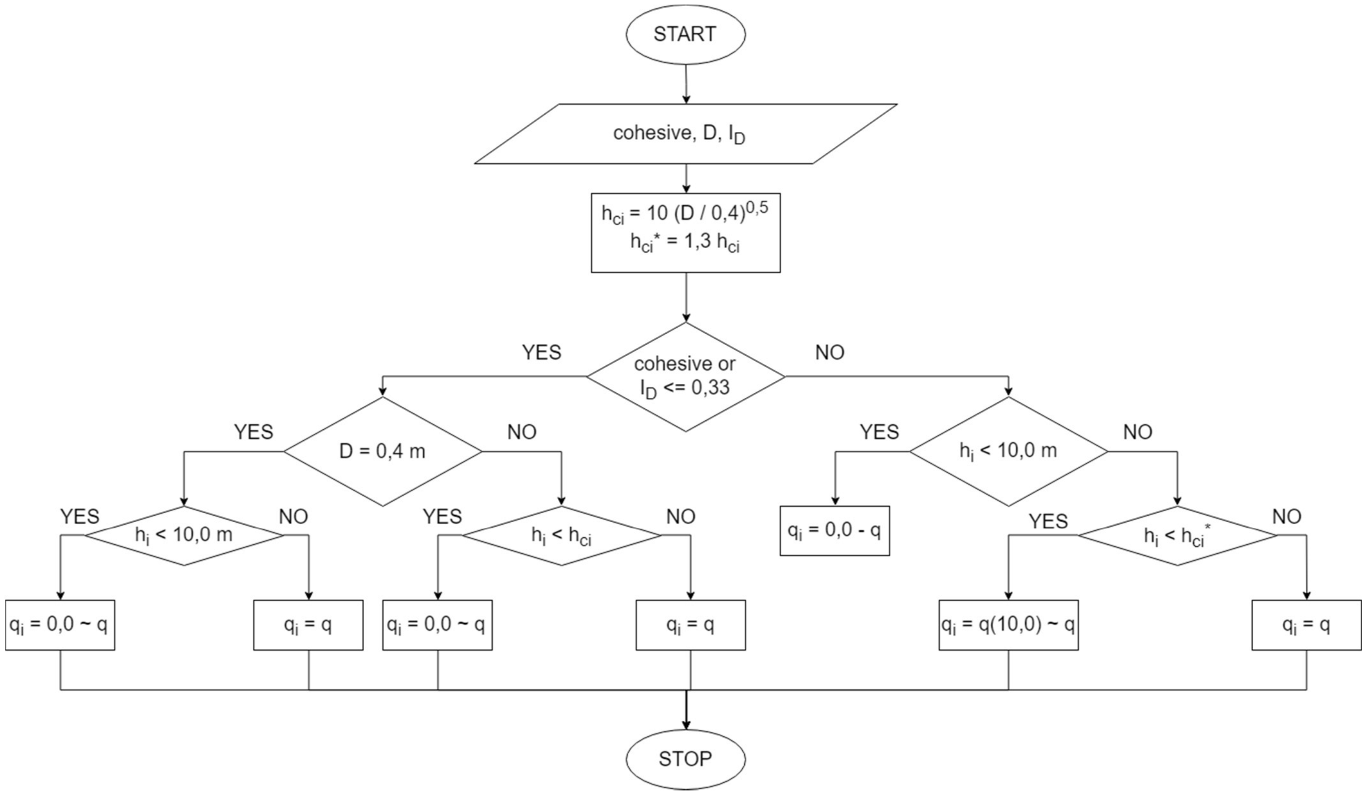
Characteristic value of the unitary resistance of the pile base for given layer:

$$q_{b,k} = S_p \cdot q^{(n)}$$ *(PN-B-02482, equation 2)*

Characteristic value of the unitary resistance of the pile side in layer *i*:

$$q_{s,i,k} = S_{Si} \cdot t_i^{(n)}$$ *(PN-B-02482, equation 2)*

Interpolation of q value ("~" means linear interpolation):



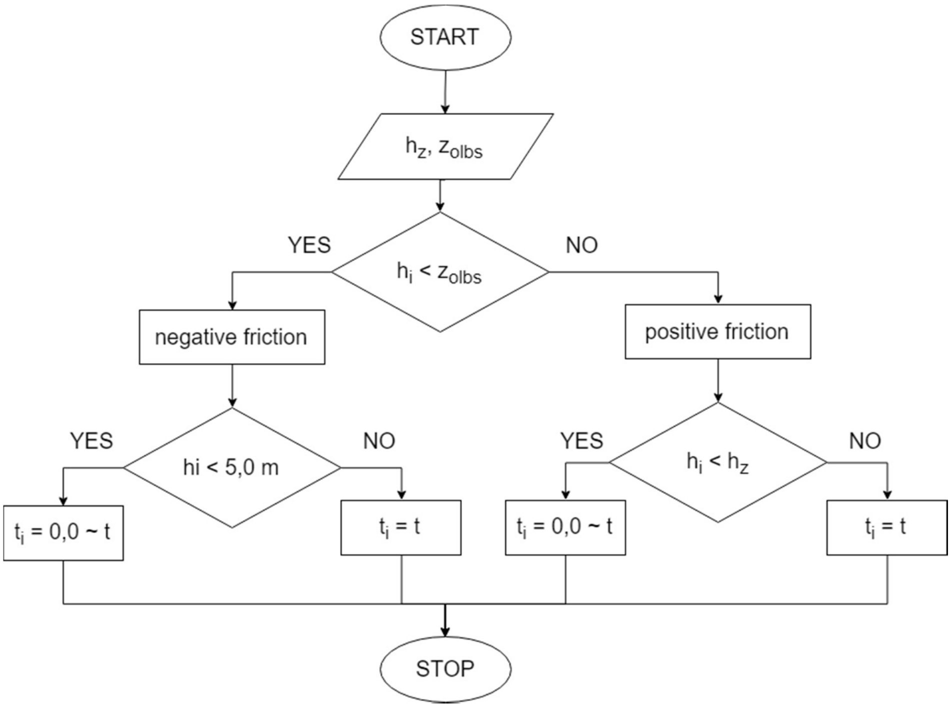
Algorithm 3 Interpolation of coefficient q

Ordinate of ceiling of load-bearing soil layer

$$h_z = \frac{0{,}65 \cdot \sum(\gamma_i h_i)}{\gamma_i} \qquad \textit{(PN-B-02482, equation 7)}$$

Non-load bearing layers which causes compaction relative to the pile can cause also negative friction in layers above non-load bearing layer.

Interpolation of t value("~" means linear interpolation) :



Algorithm 4 Interpolation of coefficient t

Design value of negative friction:

$$Tn_d = \sum_{i=1}^{n} A_{s,i} t_{d,i}$$

Design value of the shaft resistance of a pile with taking into account design value of negative friction:

$$R_{s,d,cal} = R_{s,d} - Tn_d$$

Design load capacity with taking into account design value of negative friction:

$$R_{c,d,cal} = R_{b,d} + R_{s,d,cal}$$

To obtain axial load for a pile is needed to calculate force for each pile. The calculations were made using the rigid foundation slab method [1]:

$$F_{c,d\_max} = max\left\{\frac{\mathrm{V_{all,d}}}{N} \mp \frac{M_{all,d} \cdot x_i}{\sum_{i=1}^{n} x_i^2)}\right\}$$

Load capacity for group of pile:

$$R_{c,d,GP} = N\ (R_{b,d} + m_1 \cdot R_{s,d} - Tn_d) \qquad \textit{(PN-B-02482, equation 14)}$$

To obtain coefficient m_1 should be calculated R:

$$R = \frac{D}{2} + \sum_{i=1}^{n} h_i \cdot tan\alpha_i$$

2.5. Design load capacity for horizontal forces

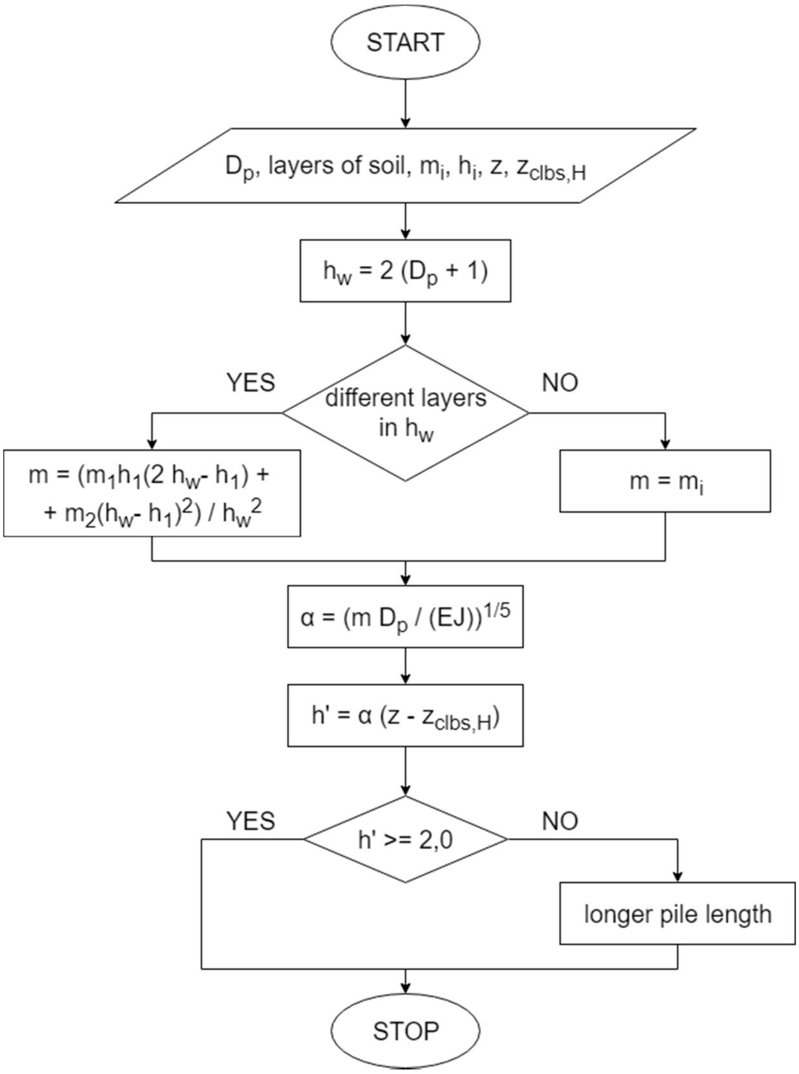
To the calculation has been used Zawrijew modified method according to the [3]. The calculations can only be made if the pile is buried at least 3,5 m from computational ordinate of load bearing soils.

The design value of pile diameter is:

- for $D_p \leq 1{,}0\ m$:
  $D_p = 0{,}9\ (1{,}5\ D + 0{,}5)$
- for $D_p > 1{,}0\ m$:
  $D_p = 0{,}9\ (1{,}5\ D + 1{,}0)K$

Where K is dependent on the number of piles in a row parallel to bending direction.

The coefficient m is taken depending on the occurrence of layers with different deformability. :



Algorithm 5 Calculation of α

This method of the calculation is valid only for situation when h' < 5,0.

Horizontal displacement at the level of the calculated ceiling level of load-bearing soil:

$$y_0 = \frac{A_y\, H_{1,k}}{\propto^3\, EJ} + \frac{(B_y\, M_{1,k})}{\propto^2\, EJ}\ and\ y_0 \leq 0{,}01\ m$$

Angle of rotation at the level of the calculated ceiling level of load-bearing soil:

$$\varphi_0 = \frac{A_f H_{1,k}}{\propto^3\, EJ} + \frac{(B_f\, M_{1,k})}{\propto^2\, EJ} and\ \varphi_0 \leq 0{,}02$$

Horizontal displacement of the head of pile:

$$y = y_0 + h_H\, \varphi_0$$

Horizontal displacement of the whole construction

$$y_{kon} = y_0 + (h_H + h_{kon})\, \varphi_0$$

Bending moment force in pile:

$$M_{z,d} = \frac{A_m\, H_{1,d}}{\propto} + B_m\, M_{1,d}$$

Lateral pressure on the ground:

$$p_{z,d} = \frac{A_{pH}\, H_{1,d} \propto}{D_p} + \frac{B_{pM}\, M_{1,d} \propto^2}{D_p}$$

Lateral boundary resistance:

$$r_{z,k} = \beta\, S_n\, (\sigma'_{v,0,z,k}\, K_q + 0{,}4\, c\, K_c)$$

2.6. Vertical settlement of pile

It is assumed that the geostatic stresses from external forces propagate only in the soil layers that carry the load. The ground is loaded with a virtual foundation foot which has the dimensions of the base B_G x L_G and is located at the depth of the end of foundation piles. Subsequent settlement calculations are carried out for layers with a thickness of 2 m.

Effective characteristic value of total concentrated load:

$$F'_k = V_{G,k} + V_{Q,k} + V_{stem,k} + V_{slab,k} + N\, V_{pile,k}$$

Primary effective geostatic stress:

$$\sigma_{v,0,z,k} = \sum h_i\, \gamma'_{i,k}$$ *(PN-B-03020 equation 16)*

Additional effective geostatic vertical stress:

$$\sigma_{v,d,z,k} = \eta_s\, \sigma'_{v,d,o,k}$$ *(PN-B-03020 equation Z2-9)*

$$\eta_s = \frac{2}{\pi}\left(arctg\left(\frac{\frac{L_G}{B_G}}{\frac{z}{B_G}\sqrt{1+\left(\frac{L_G}{B_G}\right)^2+\left(\frac{z}{B_G}\right)^2}} \right) + \frac{\frac{z}{B_G}}{\frac{L_G}{B_G}}\left(\sqrt{1+\left(\frac{z}{B_G}\right)^2} + \sqrt{\left(\frac{L_G}{B_G}\right)^2+\left(\frac{z}{B_G}\right)^2} + \sqrt{1+\left(\frac{L_G}{B_G}\right)^2+\left(\frac{z}{B_G}\right)^2} - \frac{z}{B_G} \right) \right)$$

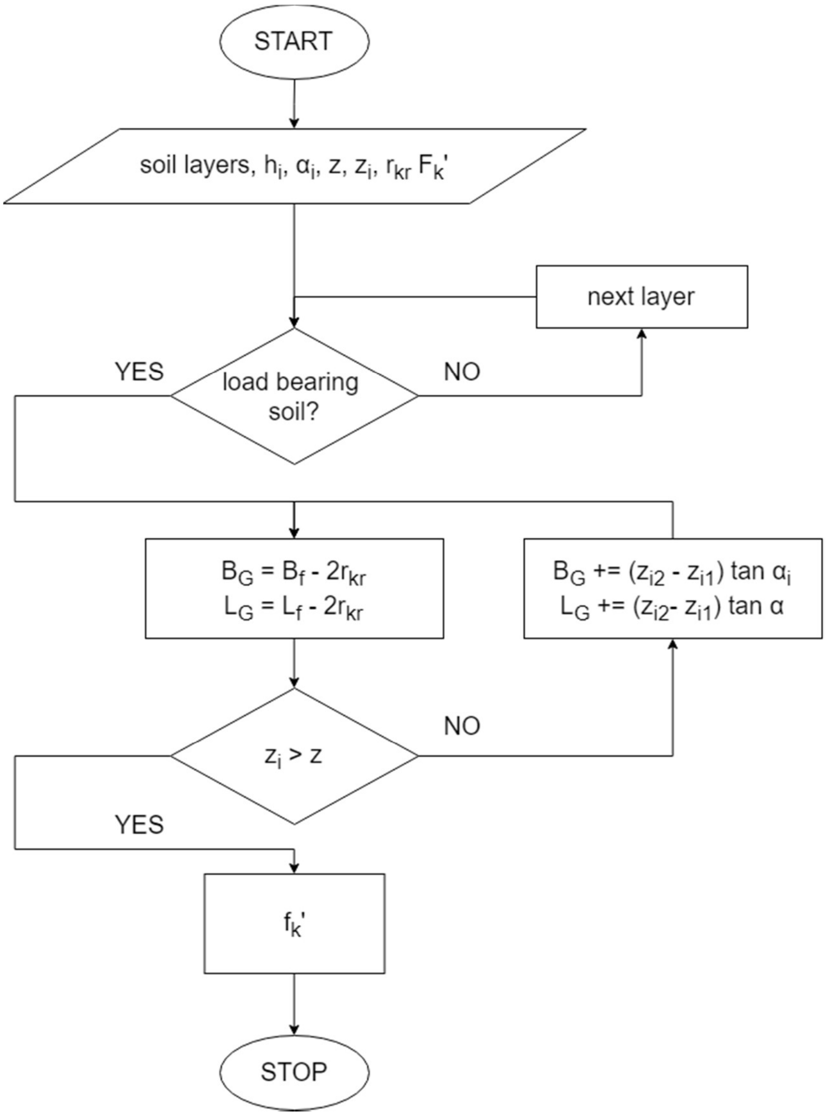
(PN-B-03020 equation Z2-9)

Average foundation settlement:

$$s_{sr} = \frac{\sum_{i=1}^{n} \sigma'_{v,d,i,k}\, h_i}{M_{0,k}}$$

(PN-B-03020 equation 21)

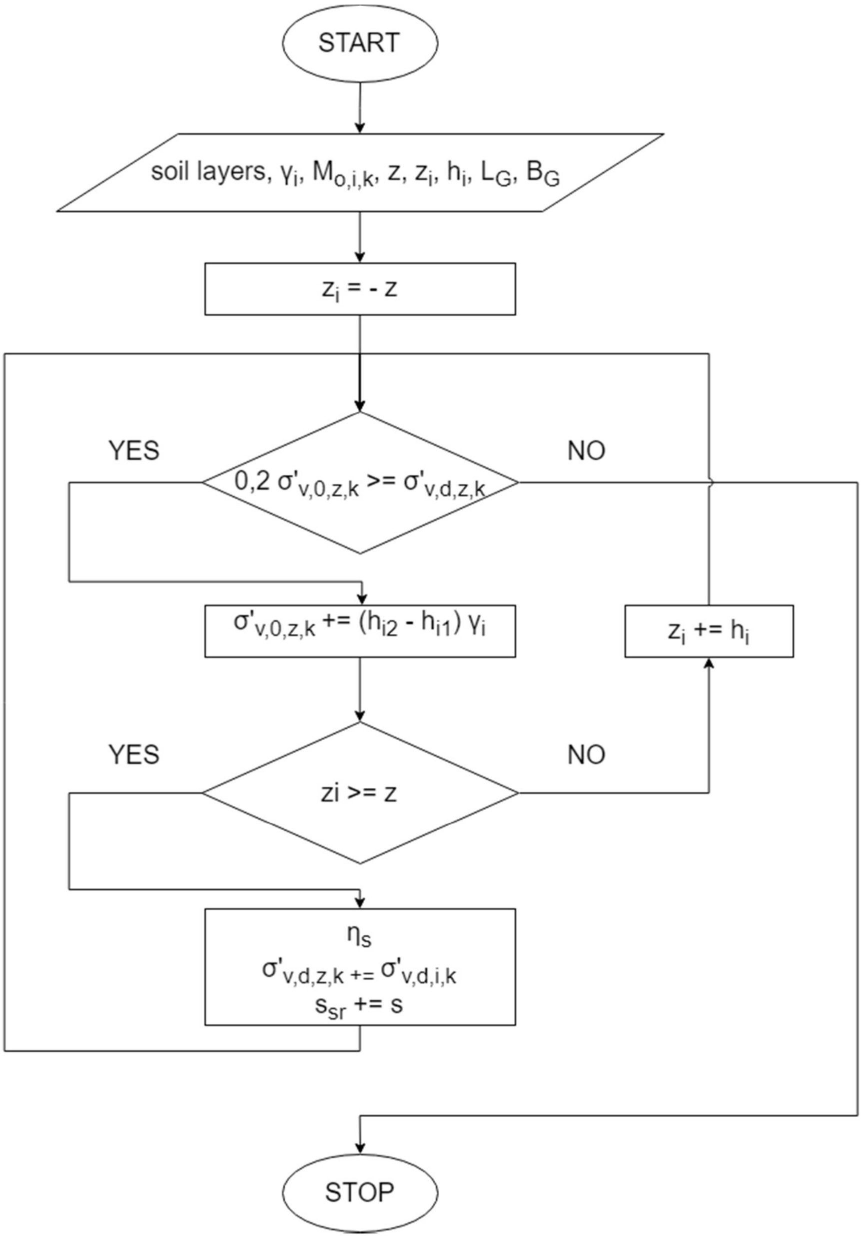
Calculation of the dimensions of the virtual spread footing:



Algorithm 6 Calculation of virtual dimensions of foundation slab

This method of the calculation is valid only for situation when h' < 5,0.

Effective primary geostatic stresses and vertical additional stresses:



Algorithm 7 Calculation of virtual settlement of pile

2.7. Reinforcement of pile

There are several rules, which must be considered in reinforcement designing.

Min. reinforcement area:

- $A_c \leq 0{,}5\ m^2$ — $A_s \geq 0{,}5\% \times A_c$
- $0{,}5\ m^2 \leq A_c \leq 1{,}0\ m^2$ — $A_s \geq 25\ cm^2$
- $A_c \geq 1{,}0\ m^2$ — $A_s \geq 0{,}25\% \times A_c$

Main bars:

- Min. reinforcement — 4x 12 mm
- Min. bars spacing — ≥ 10 cm
- Max. bars spacing — ≥ 40 cm
- Min. reinforcement area — $A_s \geq 0{,}5\% \times A_c$

Transversal reinforcement area:

- Min. bars diameter — ≥ 6 mm
  ≥ 0,25 × main bars diameter

When proceeding with structural calculations of a circular cross-section of piles, the following approximation of the shape of the pile cross-section may be used:

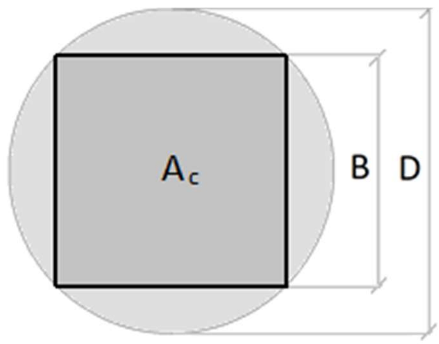


Fig. 1 pile shape approximation

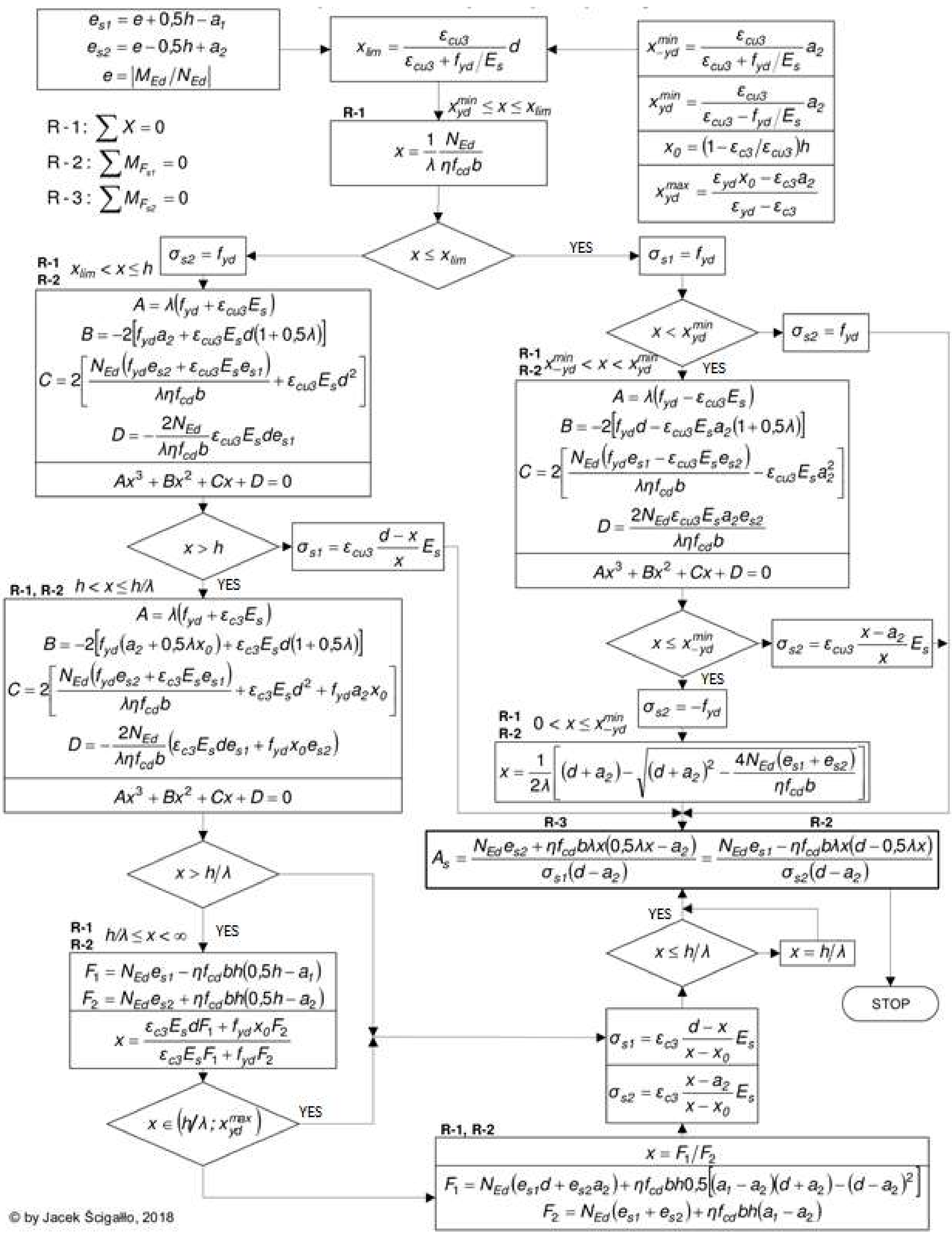
It is calculated with such formula:

$$B = \frac{D}{\sqrt{2}}$$

Cross-section area:

$$A_c = B^2$$

Next the element is calculated as a beam compressed eccentrically



Algorithm 8 Check the reinforcement strength

2.1. Reinforcement of slab

The minimum area of reinforcement in a slab must be calculated in both directions. When it is already computed, it is compared with provided reinforcement.

Calculation value of the bending moment in the plate in the middle of the span X (B):

$$M_{x,d} = R_{c,d} \sum_{i=1}^{n} y_i$$

Strength in reinforcement along the X direction (B):

$$Z_x = \frac{M_{x,d}}{d_x}$$

Surface of reinforcement stretched over the X direction (B):

$$A_{s,x} = \frac{Z_x}{f_{yd}}$$

The minimum area of reinforcement stretched over the direction X (B) per meter:

$$A_{s,min,x} = \frac{A_{s,x}}{L_f}$$

A slab is also analyzed in terms of puncture resistance without additional reinforcement.

Stresses in the slab caused by the soil pressure acting on the foundation, reduced by the foundation's own weight:

$$p = \frac{\gamma_g V_{G,k} + V_{Q,d}}{B_f L_f}$$

Surface area of the considered control area:

$$A_0 = c_1 \times c_2$$

Net force directed upwards, operating within the limits of the considered control area:

$$\Delta V_{Ed} = p \times A_0$$

Computational value of net vertical force:

$$V_{Ed,red} = V_{Ed} - \Delta V_{Ed}$$

Average tangential stresses:

$$v_{Ed} = \frac{V_{Ed,red}}{ud_{eff}}\left(1 + k\,\frac{M_{Ed}u}{V_{Ed,red}W_1}\right)$$

Reduction coefficient of concrete shear strength:

$$v = 0{,}6(1 - \frac{f_{ck}}{250}$$

Maximum tangential stresses:

$$v_{Rd,max} = 0{,}5 v f_{cd}$$

3. Tools supporting the design of foundation piles

3.1. Programming environment

The foundation pile design module is written in the Python programming language. They act as an additional dimensioning rule for the node elements of the Soldis PROJEKTANT program.

3.1.1 Python language

Python is an interpreted, interactive programming language created by Guido van Rossum in 1990. It has a fully dynamic type system and automatic memory management, so it is similar to Tcl, Perl, Scheme or Ruby. Python is being developed as an Open Source project, managed by a non-profit Python Software Foundation. [S3]

3.1.2 Soldis PROJEKTANT

Soldis PROJEKTANT is an easy and intuitive tool for creating and analyzing building structures, which is widely used by design offices and students from all major technical universities in Poland. The program consists of a number of complex modules within one computing environment. Each module is responsible for a part of the program's functionality. [S1]

3.2. Additional dimensioning modules in the Soldis PROJEKTANT software

Soldis PROJEKTANT gives the opportunity to create your own dimensioning rules based on Soldis DeveloperDoc documentation and creator support. In this work two dimensioning rules have been created: poles and composite beams. The modules collect information about the object from the program: element length, cross-sectional forces and characteristics of cross-sections containing two materials. Other variables are entered by the user in the dialog. The modules were created in version 8.9.1 of the Soldis PROJEKTANT program.

3.3. Project design conditions

Created modules are used to calculate the bearing capacity of foundation piles. They require proper preparation of the model.

The project must have a vertical beam element (column) transferring the construction loads to the foundation. The rule of dimensioning "foundation piles" should be applied to the lower end of this element. In the window that opens, one should give properties to individual layers of the ground, starting at the highest one. Then set the ground water level. On such a prepared model, we can start to design foundation piles.

3.4. Module installation manual

The installation consists in copying to the Design\lib\components\node directory located in the root directory of the Soldis PROJEKTANT program the FoundationPiles folder

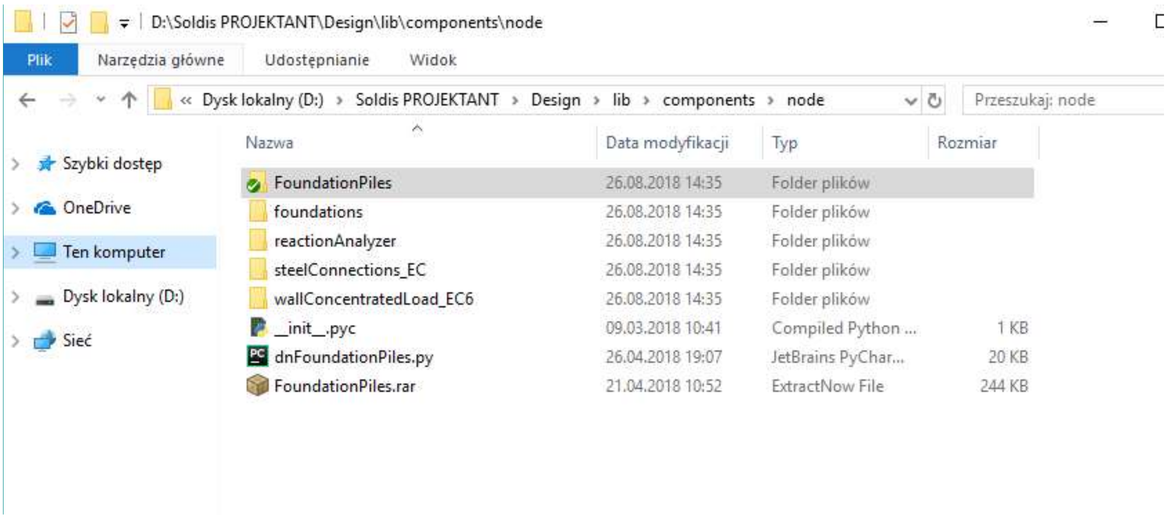


Fig. 2 Modules folder directory

Then in the *components.txt* file located in *Design\lib directory add*:

- *components. node.FoundationPiles.dnFoundationPiles$FoundationPiles$*

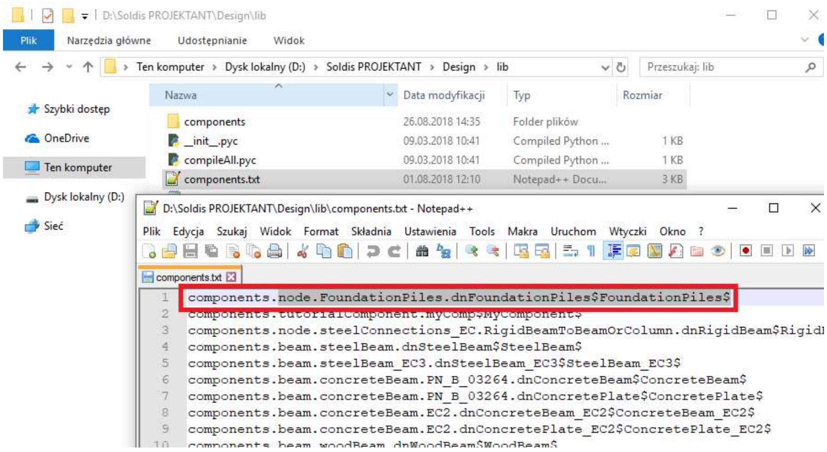


Fig. 3 Module installation

3.5. Module designing manual

To proceed with the calculation of the bearing capacity of a composite element, turn on the Soldis PROJEKTANT program. Next, you need to create a statically stable system of bars in it, apply loads to it and create their combinations. Then select the “Design” button in the “Analysis” tab, click “Assign design rule” and start the appropriate module from the list.

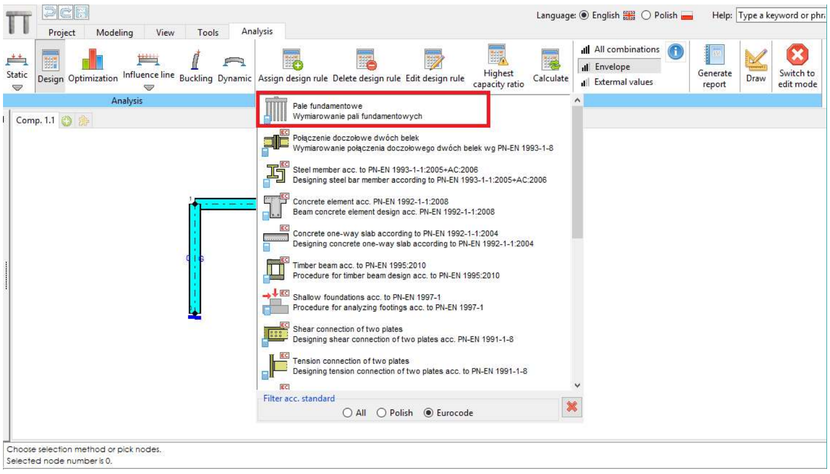


Fig. 4 The dimensioning rule selection

Then select the appropriate node and confirm with the Apply button, which results in the appearance of the dimensioning dialog box.

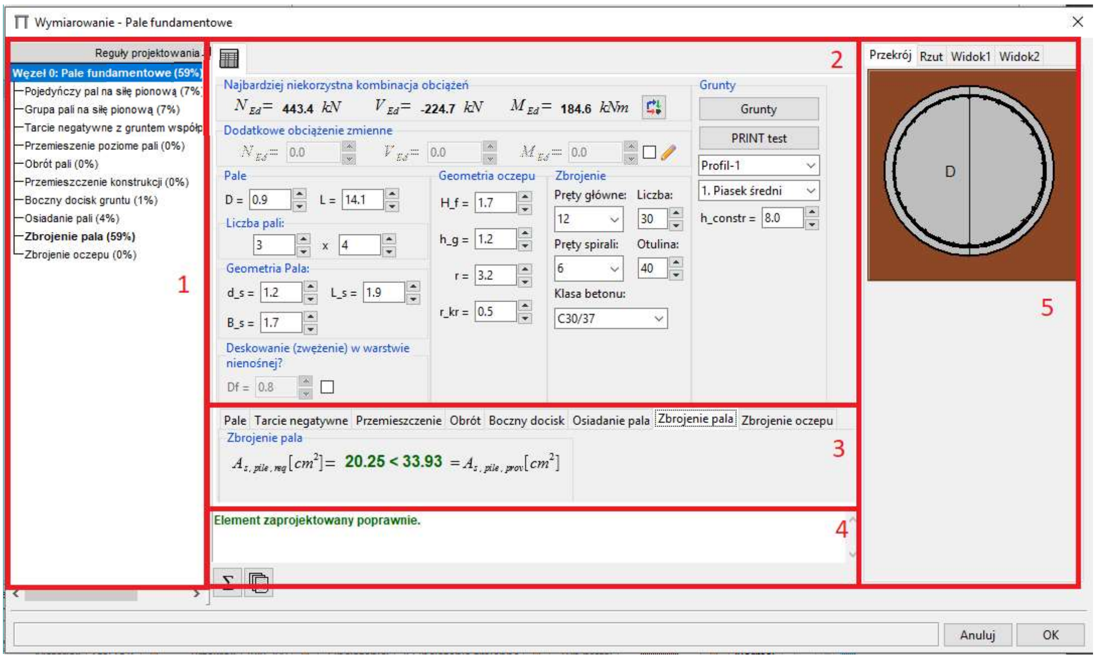


Fig. 5 Foundation Piles User Interface

The User Interface consists of 5 main panels displaying results and allowing the user to enter project data.

1. The 1st panel shows the load conditions and the percentage ratio in the most unfavorable combinations.
2. The 2nd panel contains parameters modified by the user regarding the section geometry and material characteristics.
3. The 3rd panel presents load and strength values for particular strength conditions.
4. The 4th panel is responsible for displaying design errors and additional information. It has buttons for generating a report and selecting a combination.
5. The 5th panel shows foundation piles in different views

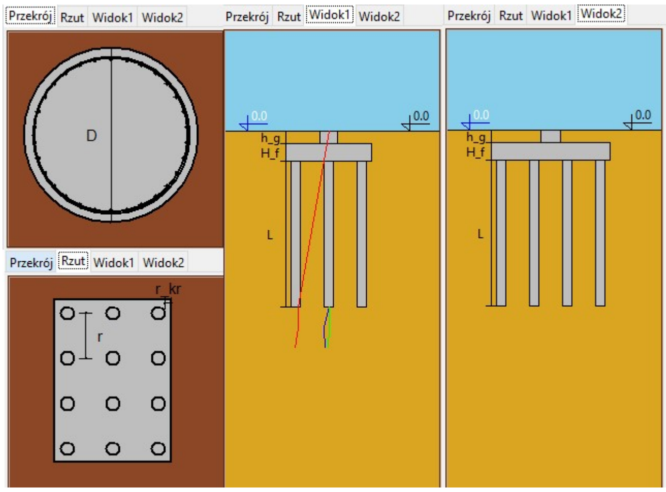


Fig. 6 Views of foundation piles

In order to import new types of land created for the purpose of calculating foundation piles, you must also delete the existing sdSoil.py file and replace it with the new one attached to the program - it should be placed in the main Soilds' folder.

4. Example of calculations

In order to verify calculation of proposed algorithms, the results from program were compared with the results from subject examples

Example 1

The comparison of the foundation pile modeled in the program to the calculation example carried out as part of project exercises.

Basic parameters:

- diameter of pile — D = 1000 mm
- length of pile — L = 14,1 m
- number of piles — N = 12
- distance between piles — r = 3,2 m
- height of foundation slab — H_f = 1,7 m
- distance between ground and slab — h_{ground} = 1,2 m

Below is a diagram of the foundation and type of soil layers.

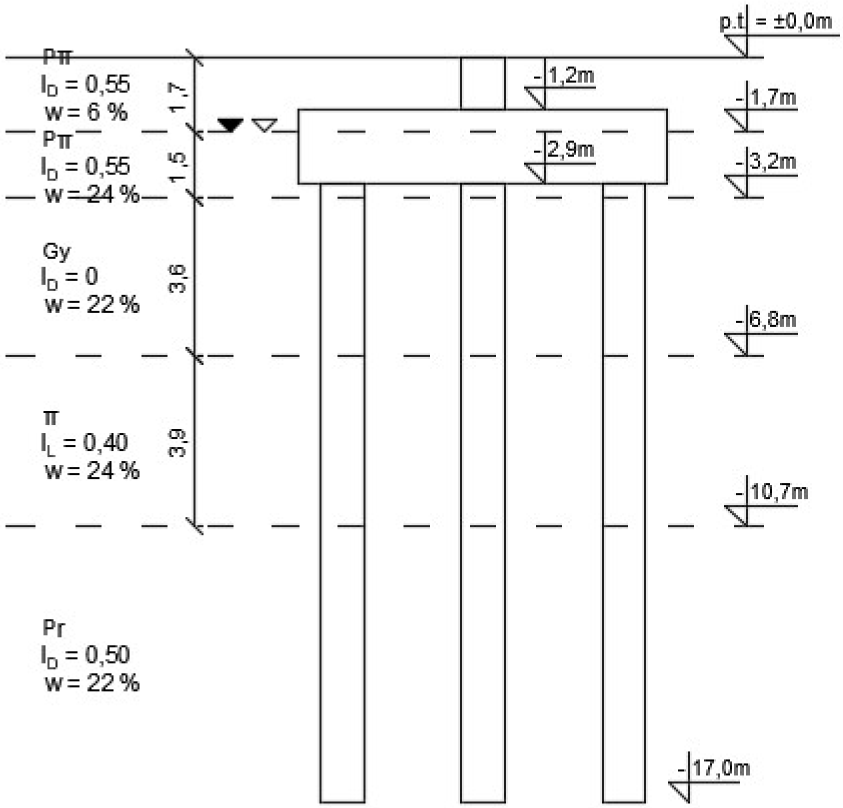


Fig. 7 Layers of soils and foundation pile

Below, a comparison of the coefficients determining the load bearing capacity of the pile base and its side was presented.

The values of the coefficient q:

No.	Type of soil	Value from the program	Value from example	Percentage difference
1.	Pπ	1764,7 kPa	1764,7 kPa	0 %
2.	Pπ	1746,7 kPa	1746,7 kPa	0 %
3.	Gy	0,0 kPa	0,0 kPa	0 %
4.	Π	650,0 kPa	650,0 kPa	0 %
5.	Pr	2875,0 kPa	2875,0 kPa	0 %

Table 1 Coefficient q value

The values of the coefficient t:

No.	Type of soil	Value from the program	Value from example	Percentage difference
1.	Pπ	37,9 kPa	37,9 kPa	0 %
2.	Pπ	37,9 kPa	37,9 kPa	0 %
3.	Gy	10,0 kPa	10,0 kPa	0 %
4.	Π	18,7 kPa	18,8 kPa	0 %
5.	Pr	60,5 kPa	60,5 kPa	0 %

Table 2 Coefficient t value

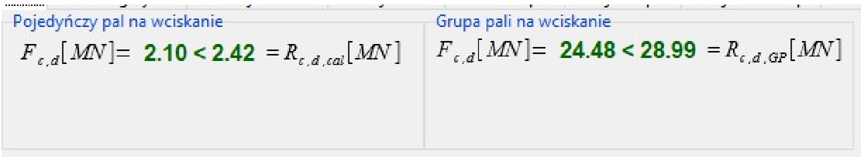


Fig. 8 Results from program

Fig. 9 Results from program

Basic load bearing values:

	Value from the program	Value from example	Percentage difference
$F_{c,d}$	2,10 MN	2,18 MN	4 %
$R_{c,d,cal}$	2,42 MN	2,57 MN	6 %
$F_{c,d,GP}$	24,48 MN	23,39 MN	5 %
$R_{c,d,GP}$	28,99 MN	30,85 MN	6 %
$Q_{Tn,k}$	1,13 MN	1,09 MN	3 %
$P_{z,d}$	18,37 kPa	17,33 kPa	6 %
$r_{z,d}$	93,69 kPa	90,86 kPa	3 %

Table 3 Comparison of load bearing capacity of foundation pile

Differences occurring at forces and load capacities are caused by differences in the weights of particular soil types. Another reason is also the error associated with reading some of the coefficients from graphs that do not have the exact functions describing the curves. The largest difference related to the pile bearing capacity for the pile group is related to reading higher values of the stress zone angle for individual layers

Example 2

The comparison of the foundation pile modeled in the program to the calculation example in [2]. This example

Basic parameters:

- diameter of pile D = 600 mm
- length of pile L = 8,42 m
- number of piles N = 2
- distance between piles r = 2,0 m
- height of foundation slab H_f = 0,7 m
- distance between ground and slab h_{ground} = 1,35 m

Below is a diagram of the foundation and type of soil layers.

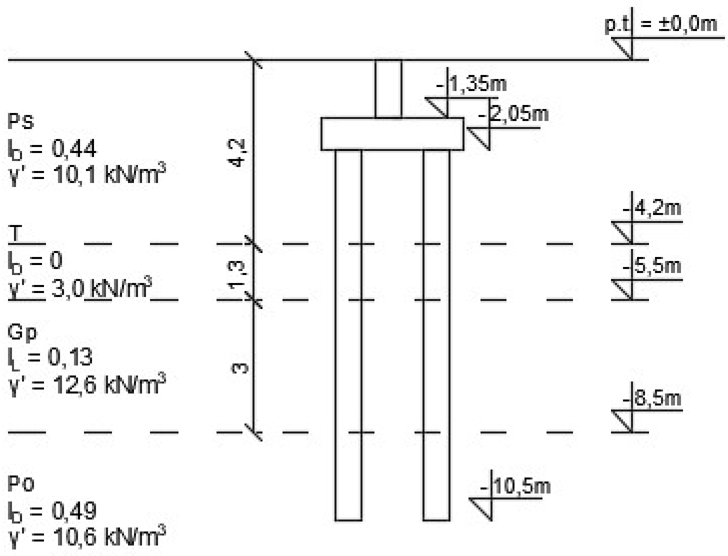


Fig. 10 Layers of soils

Below, a comparison of the coefficients determining the load bearing capacity of the pile base and its side was presented.

The values of the coefficient q:

No.	Type of soil	Value from the program	Value from example	Percentage difference
1.	Ps	2619,1 kPa	2619,1 kPa	0 %
2.	T	0,0 kPa	0,0 kPa	0 %
3.	Gp	1664,0 kPa	1664,0 kPa	0 %
4.	Po	3988,2 kPa	3988,2 kPa	0 %

Table 4 Coefficient q value

The values of the coefficient t:

No.	Type of soil	Value from the program	Value from example	Percentage difference
1.	Ps	55,7 kPa	55,7 kPa	0 %
2.	T	10,00 kPa	10,0 kPa	0 %
3.	Gp	45,0 kPa	45,0 kPa	0 %
4.	Po	90,9 kPa	90,9 kPa	0 %

Table 5 Coefficient t value

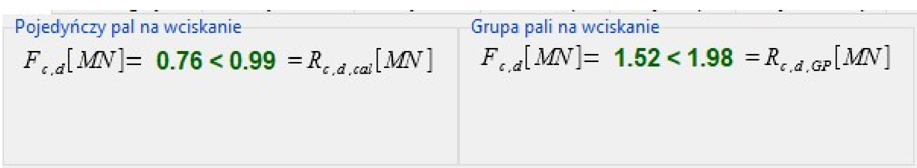


Fig. 11 Results from program

Basic load bearing values:

	Value from the program	Value from example	Percentage difference
$F_{c,d}$	0,76 MN	0,78 MN	3 %
$R_{c,d,cal}$	0,99 MN	0,92 MN	7 %
$F_{c,d,GP}$	1,52 MN	1,56 MN	3 %
$R_{c,d,GP}$	1,98 MN	1,84 MN	7 %

Table 6 Comparison of load bearing capacity of foundation pile

As in the previous case, the load capacity and forces differ for each other. It is worth noting that in the case of pile weights in the group, the coefficient m_1 = 1, which means that stress zones do not overlap - it means that each pile has full bearing capacity.

For this example, calculations for the load and side load capacity of the pile have not been carried out.

5. Summary

he result of this master thesis is a program supporting the design of foundation piles. The dimensioning rule is an extension to the Soldis PROJEKTANT program and enables quick and easy design of deep foundations in the form of group of foundation piles. At the next stage of the program development, it would be necessary to add dimensioning of other types of piles and to generate a full calculation report.

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