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1. **INTRODUCTION**

   The forGeo PaleKx application version 5.0 has been designed to enable the user to calculate the internal forces and displacement of any pile foundation with co-operation of subsoil according to the M. Kosecki’s proposal – Static analysis of pile foundations, The rules of calculating piles constructions using general method, Poland, Szczecin 2006 (original title: ‘Statyka ustrojów palowych, Zasady obliczania konstrukcji palowych metodą uogólnioną’, Polska, Szczecin 2006r.). The program also calculates load carrying capacity of pile core.

2. **TERMINOLOGY**

   The following terms have been used in the further part of the manual:

   - **program** – forGeo PaleKx version 5.0
   - **general method** – Static analysis of pile foundations, The rules of calculating piles constructions using general method, Poland, Szczecin 2006 (original title: Statyka ustrojów palowych, Zasady obliczania konstrukcji palowych metodą uogólnioną, Polska, Szczecin 2006r.)

3. **APPLICATION USAGE**

   The program has been designed to calculate the internal forces and displacement of any pile foundation with co-operation of subsoil. Calculations are performed with taking into account soil plastic phenomenon and reflects real co-operation of pile foundation with subsoil.

   The program performs calculations in accordance with the M. Kosecki’s general method, A. Krasiński’s comments to the method and a proposal of program’s author – Jakub Kowalski.

   The program generates a structure of horizontal spring supports arranged along the axis of pile and corresponding ultimate horizontal soil response. Analysis of soil plastic phenomenon is made iteratively by comparing values of horizontal reactions with ultimate horizontal soil response.

   The program includes author’s **the scheme of pile foundation** which enables user to perform the calculation subsequently for several directions of the horizontal load and different pile spacing. The scheme of pile foundation reflects **real pile arrangement** in the designed foundation.
The program also calculates load carrying capacity of pile core. The calculations of reinforcement of pile are performed in variants for different diameters of reinforcement bars. This allows the optimal selection of the type of pile reinforcement for analysed loads combinations.

The calculation results are being presented graphically. There are contained ground parameters (distribution of module of horizontal stiffness of soil and ultimate horizontal soil resistance) and graphs of results (distribution of bending moment, horizontal force, pile displacement and load carrying capacity of pile core).

What's more, the application is compatible with program forGeo PalePN which enables user to calculate pile bearing capacity based on PaleKx data.
4. DATA ENTRY – DATA TAB

Soil parameters

| Calculation title | – the title describing the analyzed soil profile/project |
| Ground ordinate | – the ordinate of the existent ground level presented in meters above sea level. Once the ordinate of the ground is specified, the soil profile created in AutoCad will include additional elevation information i.e. above mean sea level. |

The table of soil strata:

| No | – the number of the actual soil strata (this column is generated automatically) |
| Soil type | – the proper soil stratum should be chosen from the proved list by clicking the mouse (do not type the name) |
| \( Z \ [m \ bgl] \) | – the ordinate of the bottom of soil stratum (in metres below ground level) |
| ID/IL [-] | – the density index/liquidity index of soil stratum |
| Genesis [-] | – the genesis of cohesive soil \( (A, B, C, D) \), for non-cohesive soil ‘−’ |

Symbols for cohesive soils according to PN-81/B-03020:

- A – consolidated cohesive moraine soils,
- B – other cohesive soils and non-consolidated cohesive moraine soils,
- C – other non-consolidated cohesive soils,
- D – clay, regardless of geological genesis.

The following buttons should be used when editing the table regarding soil strata:

- **New stratum (downwards arrow)** – creates another stratum, click the downwards arrow on the keyboard ↓
- **Delete stratum** – deletes the current stratum
**Insert between strata**

- inserts additional stratum between existing ones – this option should not be used for creating new stratum

**Partial factors of safety**

<table>
<thead>
<tr>
<th>Partial factors of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction angle of soil</td>
</tr>
<tr>
<td>Cohesion of soil</td>
</tr>
<tr>
<td>Unit weight of soil</td>
</tr>
</tbody>
</table>

Partial factors of safety have been determined for the following physical features of soil: friction angle, cohesion and unit weight of soil. There is a possibility to modify default values of each individual factor.

- **Partial factor of safety for friction angle of soil** $\phi$ – the default value of the factor is 1.00.
- **Partial factor of safety for cohesion soil** $c$ – the default value of the factor is 0.40.
- **Partial factor of safety for unit weight of soil** $\gamma$ – the default value of the factor is 0.90.

**Global factors of safety**

<table>
<thead>
<tr>
<th>Global factors of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal stiffness of soil $Kx$</td>
</tr>
<tr>
<td>Horizontal soil response $Rgr$</td>
</tr>
<tr>
<td>Coeff of passive pressure $Kp$</td>
</tr>
</tbody>
</table>

The following global factors of safety for: horizontal stiffness of soil, maximum horizontal soil response and passive pressure have been used:

- **Global factor of horizontal stiffness of soil** $Kx$ – the default value of the factor is 1.00.
- **Global factor of maximum horizontal soil response** $Rgr$ – the default value of the factor is 1.00.
- **Global factor of horizontal passive pressure** $Kp$ embracing the simplification that the flat slide plane is adopted $\eta$ – the default value of the factor is 0.85.

There is a possibility to modify default values of each individual factor.

**Groundwater**

<table>
<thead>
<tr>
<th>Groundwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

- no groundwater
- Ordinate of phreatic level of water
If the groundwater occurs it is necessary to provide the ordinate of the phreatic water table. It follows that for the soil stratum occurring below the phreatic water table, the unit weight of submerged soil $\gamma'$ shall be applied.

**Pile parameters**

![Pile parameters](image)

**Type of pile** – the type of the pile must be defined. The program allows choosing the following foundation piles from the list:

- precast concrete pile
- steel tube pile closed base
- steel tube pile opened base
- drill pile without base injection
- drill pile with base injection
- Vibro
- Vibrex
- Fundex
- Franki
- CFA
- Atlas
- Omega
- Tubex

**Method of pile embedment** – the method of pile embedment should be defined in case one chose the following positions from the above list: user pile, precast pile (concrete, made from steel sections) or bored pile. The method of pile embedment for the remaining piles has been automatically defined by the proper type of pile (e.g. pile CFA – bored, ATLAS – driven, etc.). The program allows choosing the following methods of pile embedment of the foundation piles:

- driven pile
- vibration driven pile
- water jet driven (last 1m hammer driven)
- cast-in-place, support fluid
- cast-in-place, casing extracted
- cast-in-place, casing left in place
- cast-in-place, casing rotary-extracted
- cast-in-place, rotary-suction with water-jet

**The value of the pile-soil friction angle** – define the friction angle towards the pile and soil $\delta$ with reference to the soil friction angle $\phi$. There is a possibility to modify the default coefficient values of cohesive and non-cohesive soil.

**Temporary construction** – define the use of the pile foundation. If the foundation is a temporary construction, the default value of the coefficient for long-lasting or cyclic loads effect $\varphi$ is 1.00. Otherwise the coefficient $\varphi$ is applied according to the Kosecki’s recommendation.

**Pile diameter / pile width** – for piles with a circular cross section the pile diameter should be provided, for piles with a square cross section the breadth of the pile side (width) should be defined.

**Pile length** – define the pile length measured from the foundation bottom to the pile base.

**Ordinate of foundation bottom** – define the ordinate of foundation bottom.

**Concrete grade** – define the concrete grade of pile. The default value of the concrete grade is C25/30.

**Steel grade** – define the concrete grade. In the case of concrete piles the steel grade refers to strength of the reinforcing bars and in the case of steel tube piles for strength of the tube. The default value of the steel grade is S 500 (i.e. for reinforcement bars).

**Factors for materials properties** – button allows displaying the factors of materials for concrete and steel.

- Partial factor for steel $\gamma_s$ 1.15
- Partial factor for concrete $\gamma_c$ 1.40
- Reduction factor for construction of special significance $\alpha_{cc}$ 1.00
5. **PILES FOUNDATION PARAMETERS – FOUNDATION TAB**

**Soil and pile parameters** – once the following parameters have been defined in the tab ‘Data’: the soil type, density/liquidity index (including the genesis of cohesive soil) as well as the type and method of pile embedment, the program automatically generates subsequent parameters: \( \gamma, \gamma', \phi, \delta, c, E_0 \) in accordance with PN-81/B-03020 while \( S_n \) and \( \varphi \) compliant with the general method. The user can **freely modify** all standardized values of the parameters. Once the parameter has been changed there is a possibility to restore the default (standard) value.

<table>
<thead>
<tr>
<th>Table of soil and pile parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No</strong> – reference number of the soil stratum</td>
</tr>
<tr>
<td><strong>Soil type</strong> – type of the soil</td>
</tr>
<tr>
<td><strong>( \gamma ) [kN/m3]</strong> – unit weight of soil</td>
</tr>
<tr>
<td><strong>( \gamma' ) [kN/m3]</strong> – buoyancy unit weight of soil (unit weight of submerged soil)</td>
</tr>
<tr>
<td><strong>( \phi ) [(^\circ)]</strong> – friction angle of soil</td>
</tr>
<tr>
<td><strong>( \delta ) [(^\circ)]</strong> – pile-soil friction angle</td>
</tr>
<tr>
<td><strong>c [kPa]</strong> – cohesion of soil</td>
</tr>
<tr>
<td><strong>E_0 [MPa]</strong> – initial soil deformation modulus (Young’s Modulus of soil)</td>
</tr>
<tr>
<td>( E_0 = \frac{(1 + \nu) \cdot (1 - 2\nu)}{1 - \nu} \cdot M_0 )</td>
</tr>
<tr>
<td>( \nu ) – Poisson's ratio</td>
</tr>
<tr>
<td>( M_0 ) – oedometer modulus (( E_{oed} ))</td>
</tr>
<tr>
<td><strong>Sn [-]</strong> – coefficient for the method of pile embedment (soil structure disturbance when embedding the pile)</td>
</tr>
<tr>
<td><strong>( \varphi ) [-]</strong> – coefficient for long-lasting or cyclic loads effect</td>
</tr>
</tbody>
</table>
Scheme of the pile foundation

The program includes an innovative and original scheme of pile foundation which allows making calculations of internal forces and displacement simultaneously for several directions of the horizontal load and for different pile spacing.

The scheme of pile foundation reflects real pile arrangement in the designed foundation. The scheme contains of 9 characteristic piles numbered from 1 to 9. Each number stands for a specific pile: corner, edge and inner.

![Scheme of the pile foundation](image)

The description of piles in the scheme of the pile foundation:

- **Pile # 5**
  The pile is located in the inner row and the inner column of piles. The pile No. 5 is surrounded by piles from the adjoining rows and adjoining columns – the inner pile of the pile group.

- **Piles # 2 and 8**
  The piles are located in the inner column and the outermost row of piles. The piles No. 2 and 8 are surrounded by piles from adjoining columns and are located in the outermost row of the pile group.

- **Piles # 4 and 6**
  The piles are located in the inner row and the outermost column of piles. The piles No. 4 and 6 are surrounded by piles from adjoining rows and are located in the outermost column of the pile group.

- **Piles # 1, 3, 7, 9**
  The piles are located in the outermost row and the outermost column of piles. The piles No. 1, 3, 7 i 9 are not surrounded by any piles of adjoining rows or any adjoining columns of the pile group – corner piles.
The following example presents the idea of comparing each pile in foundation of bridge pillars with characteristic piles in scheme of pile foundation. All the piles in bridge pillars were graphically matched with characteristic piles in scheme of pile foundation.

Exemplary foundation of bridge pillars contains of 29 piles however a scheme of pile foundation contains only 9 piles (corner, edge and inner). According to above, to each pile of scheme of pile foundation, a single pale as well as the whole group of piles was matched.

According to the following picture corner and edge piles No. 1÷3 and 7÷9 in scheme of foundation correspond to single piles in foundation of bridge pillars however inner piles No. 4÷6 in scheme of foundation correspond to groups of piles in foundation of bridge pillars.

**Picture no. 1.** The idea of comparing each pile in foundation of bridge pillars with characteristic piles in scheme of pile foundation.
6. DEFINITION OF CALCULATIONS – CALCULATIONS TAB

**Pile loads** – there are defined as designed loads in pile head. It was established signs convention presented on the following picture.

**Factors for loads** – button allows displaying the partial safety factors for permanent and variable loads as well as the global safety factor. Factors for loads are included in calculation of the displacement of pile to determine the characteristic values of loads.

**Partial safety factors**
- Partial safety factor for permanent loads \( \gamma_G \) 1.35
- Partial safety factor for variable loads \( \gamma_Q \) 1.50

**Global safety factor**
- Ratio of variable loads to total loads \( \frac{Q}{G+Q} \) 0.50
- Global safety factor, calculated according below formula:

\[
\gamma_{(G,Q)} = \frac{Q}{G+Q} \cdot \gamma_Q + \left(1 - \frac{Q}{G+Q}\right) \cdot \gamma_G
\]
Calculations of internal forces

The method of calculating of internal forces should be defined. Calculations with soil plastic phenomenon reflected real co-operation of pile with subsoil. Rules of calculating of internal forces with and without taking into account soil plastic phenomenon discussed in section 9.

Calculations of pile reinforcement

Scope of calculations – it is possible to perform calculations including full detailed parameters of reinforcement or basic calculations. Comparing scope of full and basic calculations set out below.

<table>
<thead>
<tr>
<th>Scope of calculations of pile reinforcement</th>
<th>Full calculations</th>
<th>Basic calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graph of load carrying capacity of pile core with</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ultimate value of bending moment and normal force:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( M_{\text{ult,max}} ) – ultimate bending moment</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>corresponding to design normal force</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_{\text{ult,nim}} , N_{\text{ult,max}} ) –</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ultimate normal forces corresponding to design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bending moment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed results for pile reinforcement:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_s1 ) – resultant stress in tension reinforcement</td>
<td>✔</td>
<td>×</td>
</tr>
<tr>
<td>( F_s2 ) – resultant stress in compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>reinforcement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( z_s1 ) – distance of resultant stress ( F_s1 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from axis of pile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( z_s2 ) – distance of resultant stress ( F_s2 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from axis of pile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varepsilon_s1 ) – deformation of reinforcement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in tension zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed results for concrete:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( x_{\text{lim}} ) – height of compression zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of section</td>
<td>✔</td>
<td>×</td>
</tr>
<tr>
<td>( F_{c1} ) – resultant compression stress in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( z_{c1} ) – distance of resultant stress ( F_c )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>from axis of pile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varepsilon_{c1} ) – deformation of concrete in</td>
<td></td>
<td></td>
</tr>
<tr>
<td>compression zone</td>
<td>✔</td>
<td>×</td>
</tr>
</tbody>
</table>
**Geometric parameters** – specify the following geometric parameters of reinforcement:

- **Concrete cover** – specify pile concrete cover. The value of concrete cover is defined by the outer edge of pile to the outer edge of stirrups (spiral of main reinforcement).
- **Stirrups diameter (spiral)** – specify diameter of stirrups (spiral of main reinforcement).
- **Minimum bar spacing (clearance between bars)** – specify the minimum allowable spacing between the bars of main reinforcement. After performing the calculations will show only those variants of reinforcement of the pile where the bar spacing is not less than the minimum spacing.

**Method of calculating reinforcement** – specify how to determine the number of reinforcement bars:

- **Calculate automatically number of bars** – then the number of bars is calculated automatically by the program. The calculation results are presented as reinforcement variants for different diameters of bar. Specify whether the calculations include only an even number of reinforcing bars or allowed the odd number of bars.
- **Define number of bars** – then the cross-section of reinforcement of pile is defined by the user. Specify the number and diameter of reinforcement bars of the pile. If the defined reinforcement does not fulfill the condition of load carrying capacity of pile core the program automatically determines the minimum number of reinforcement bars.
7. RULES FOR CALCULATING THE HORIZONTAL STIFFNESS OF SOIL AND ULTIMATE HORIZONTAL SOIL RESPONSE

7.1 HORIZONTAL STIFFNESS OF SOIL
The calculation requires indicating the value of the module of horizontal stiffness of soil \( K_x \). Additionally the program calculates also the values of the springy horizontal support in nodes arranged along the pile’s axis in spacing of 0.1m.

The value of the module of horizontal stiffness of soil \( K_x \)
\[
K_x = n_0 \cdot n_1 \cdot n_2 \cdot n_3 \cdot \kappa \cdot \varphi \cdot E_0
\]

7.2 ULTIMATE HORIZONTAL SOIL RESISTANCE
The calculation requires indicating the value of the ultimate horizontal soil resistance \( Q_r \). Additionally the program calculates also the values of the ultimate horizontal soil response in nodes arranged along the pile’s axis in spacing of 0.1m.

The value of the ultimate horizontal soil resistance \( Q_r \)
\[
Q_r = m_1 \cdot S_n \cdot n_1 \cdot n_2 \cdot n_3 \cdot D_0 \cdot \left( \sigma_i K_{ph} + c \cdot \sqrt{K_{ph}} \right)
\]

where:

- \( n_0 \) – corrective coefficient for the effect of pile diameter
- \( n_1 \) – coefficient for the spacing of piles in a group arranged in the plane perpendicular to the direction of the horizontal load
- \( n_2 \) – coefficient for the spacing of piles in a group arranged in the plane parallel to the direction of the horizontal load
- \( n_3 \) – coefficient reflecting the spatial feature of the effect of the horizontal soil resistance, it is conditioned upon the shape of the pile cross-section
- \( S_n \) – coefficient for the method of the pile embedment (the disturbance of the soil structure during the pile embedment)
- \( \kappa \) – coefficient for the spatial dimension of the soil response, it is conditioned upon the shape of the pile cross-section
- \( \varphi \) – coefficient for the long-lasting or cyclic loads effect
- \( E_0 \) – initial deformation modulus (Young’s Modulus of soil)
\[
E_0 = \frac{(1 + \nu) \cdot (1 - 2\nu)}{1 - \nu} \cdot M_0
\]

\(\nu\) – Poisson's ratio

\(M_0\) – oedometer modulus \((E_{0ed})\)

\(m_1\) – corrective coefficient comprising piles’ co-operation in a group of piles

\(D_0\) – substitute pile diameter

\(\sigma'\) – horizontal effective stress in soil

\(K_{ph}'\) – coefficient for horizontal passive pressure

\(c\) – cohesion of soil

### 7.3. COEFFICIENT FOR THE METHOD OF PILE EMBEDMENT

Coefficient for the method of pile embedment \(S_n\) includes effect of disturbance of the soil structure during pile embedment on the value of horizontal stiffness of soil and ultimate horizontal soil resistance.

Values of \(S_n\) coefficient applied in the program are accordant with the general method. The exceptions are precast piles (concrete and steel tubes) embedment in cohesive soils. In the general method the value of \(S_n\) coefficient is zero in case of vibrating and water jet driving the precast piles into cohesive soils regardless of liquidity index of soil. Regardless of soil parameters the general method assumes zero value of horizontal soil stiffness and soil resistance for vibrating and water jet driving precast piles.

However the following values of coefficient were assumed into the program:

<table>
<thead>
<tr>
<th>Pile type</th>
<th>Method of pile embedment</th>
<th>Value of (S_n) coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precast concrete pile or steel hollow section pile (closed base)</td>
<td>Vibration driven pile</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Water jet driven (last 1m hammer driven)</td>
<td>0.30</td>
</tr>
<tr>
<td>Steel hollow section pile (open base)</td>
<td>Vibration driven pile</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Water jet driven (last 1m hammer driven)</td>
<td>0.50</td>
</tr>
</tbody>
</table>
8. DIVERSITY HORIZONTAL STIFFNESS OF SOIL AND ULTIMATE HORIZONTAL SOIL RESISTANCE DEPENDING ON LOCATION OF THE PILE IN FOUNDATION

Horizontal stiffness of soil $K_x$ and ultimate horizontal soil resistance $R_{gr}$ for each foundation are diversity depending on the distance between adjacent piles. An influence of pile spacing and amount of pile in foundation included the $n_1$ and $n_2$ coefficients.

In addition, the program diversities above coefficients depending on the pile’s location in foundation – for example if pile is located in the first row or in the next row and if it is a corner or an inner pile. The rules of calculation the $n_1$ and $n_2$ coefficients described below.

According to the general method $n_1$ and $n_2$ coefficients are described by below formulas:

Coefficient $n_1$:

$$n_1 = 0.2 \cdot \frac{R_1}{D} + 0.4 \leq 1.0$$

Coefficient $n_2$:

$$n_2 = \beta + \frac{(1-\beta) \cdot (R_2 - D)}{1.8 \cdot (1.5 \cdot D + 0.5)} \leq 1.0 \quad \text{for } D < 1.0 \text{m}$$

$$n_2 = \beta + \frac{(1-\beta) \cdot (R_2 - D)}{1.8 \cdot (D + 1.0)} \leq 1.0 \quad \text{for } D \geq 1.0 \text{m}$$

where:

$D$ – pile diameter or pile width [m];

$R_1$ – axial pile spacing in the plane perpendicular to direction of the horizontal load, [m];

$R_2$ – axial pile spacing in the plane parallel to direction of the horizontal load, [m];

$\beta$ – coefficient dependent on the number of piles in a row parallel to direction of the horizontal load, [-] ($\beta = 1.0$ for one row of piles, $\beta = 0.6$ for two rows of piles, $\beta = 0.5$ for three rows of piles, $\beta = 0.45$ for four or more rows of piles).

The author’s scheme of pile foundation included in the program allows diversity stiffness of soil depending on pile’s location in foundation by including different values of $n_1$ and $n_2$ coefficients.

Description of the rules of defining the coefficient values for specific piles, which determining the stiffness of soil and ultimate soil resistance, is described in the further part of the manual.
8.1 PILE LOCATED IN THE INNER ROW AND INNER COLUMN OF PILES

It is the pile No. 5 in the scheme of pile foundation, which is surrounded by piles from the adjoining rows and columns – so-called the inner pile of the pile group.

In its simplest form the formula for \( n_1 \) coefficient equals:

\[
 n_1 = 0.2 \cdot \frac{R_1}{D} + 0.4 \leq 1.0
\]

The inner pile of the pile group (No. 5 presented in the above picture) is surrounded by adjoining piles and their axial spacing in the plane perpendicular to the direction of the horizontal load is \( R_{1a} \) and \( R_{1b} \). The program allows entering different pile spacing values \((R_{1a} \neq R_{1b})\), therefore the \( n_1 \) coefficient for pile No. 5 is being calculated as a mean value in accordance with the following formula:

\[
 n_{1,pile} = \frac{n_1(R_{1a}) + n_1(R_{1b})}{2} = \left( \frac{0.2 \cdot R_{1a}}{D} + 0.4 \right) + \left( \frac{0.2 \cdot R_{1b}}{D} + 0.4 \right) \leq 1.0
\]

In its simplest form the formula for coefficient \( n_2 \) equals:

\[
 n_2 = \beta + \frac{(1 - \beta) \cdot (R_2 - D)}{1.8 \cdot (D + 0.5)} \leq 1.0 \quad \text{for } D < 1.0 \text{m}
\]

\[
 n_2 = \beta + \frac{(1 - \beta) \cdot (R_2 - D)}{1.8 \cdot (D + 1.0)} \leq 1.0 \quad \text{for } D \geq 1.0 \text{m}
\]

As presented in the above picture the inner pile of the pile group (No. 5) is surrounded by adjoining piles, which pile spacing in the plane parallel to direction of the horizontal load effect is \( R_{2a} \) and \( R_{2b} \). The program calculates the value of \( n_2 \) coefficient on the basis of the axial spacing of piles that limit the stiffness of the pile – i.e. piles located in front of the discussed pile; in accordance with the direction of the horizontal load. Therefore, the calculation of the \( n_2 \) coefficient for the pile No. 5, including the direction of the horizontal load and depending on the \( R_{2b} \) spacing is performed in accordance with the following formulas:
8.2 PILE LOCATED INSIDE THE OUTERMOST ROW OR OUTERMOST COLUMN OF PILES

In the scheme of pile foundation these are piles No. 2, 4, 6 and 8. They are surrounded by piles of the adjoining rows or columns – so-called the edge piles of the pile group. The values of coefficients $n_1$ and $n_2$ for the pile No. 6 are presented below (the same rule applies as to the calculation of coefficients for piles No. 2, 4 and 8).

In its simplest form the formula for $n_1$ coefficient equals:

$$n_1 = 0.2 \cdot \frac{R_b}{D} + 0.4 \leq 1.0$$

The edge pile of the pile group (No. 6), as presented in the picture, is surrounded by adjoining piles and their axial pile spacing in the plane perpendicular to the direction of the horizontal load is $R_{1a}$ and $R_{1b}$. The program allows entering different values for the spacing of adjoining piles ($R_{1a} \neq R_{1b}$); therefore the $n_1$ coefficient for the edge pile No. 6 is being calculated in the same way as for the inner pile No. 5 as a mean value in accordance with the following formula:

$$n_{1,pile} = \frac{n_1(R_{1a}) + n_1(R_{1b})}{2} = \left( \frac{0.2 \cdot \frac{R_{1a}}{D} + 0.4}{2} \right) + \left( \frac{0.2 \cdot \frac{R_{1b}}{D} + 0.4}{2} \right) \leq 1.0$$

In its simplest form the formula for $n_2$ coefficient equals:

$$n_2 = \beta + \frac{(1 - \beta) \cdot (R_2 - D)}{1.8 \cdot (1.5 \cdot D + 0.5)} \leq 1.0 \quad \text{for } D \geq 1.0m$$
\[ n_2 = \beta + \frac{(1-\beta)(R_2-D)}{1.8(D+1.0)} \leq 1.0 \quad \text{for } D \geq 1.0 \text{m} \]

In the program the calculation of the value of the \( n_2 \) coefficient is dependent on the axial spacing of piles that limit the stiffness of pile – i.e. the piles located in front of the analyzed pile; in accordance with the direction of the horizontal load. As in the example for the pile No. 6, for the direction of the horizontal load there is no reduction in stiffness with regard to axial pile spacing \( R_{2b} \). Therefore the value of the \( n_2 \) coefficient for the edge pile No. 6 is 1.0.

### 8.3 PILE LOCATED IN THE OUTERMOST ROW AND OUTERMOST COLUMN OF PILES

In the scheme of pile foundation these are piles No. 1, 3, 7 and 9. They are surrounded by adjoining piles from one side only – so-called corner piles of the pile group. The values of coefficients \( n_1 \) and \( n_2 \) for the corner pile No. 3 are presented below (the same rule applies for the calculation of coefficients \( n_1 \) and \( n_2 \) for corner piles No. 1, 7 and 9).

In its simplest form the formula for \( n_1 \) coefficient equals:

\[ n_1 = 0.2 \cdot \frac{R_1}{D} + 0.4 \leq 1.0 \]

The corner pile of the pile group (No. 3), as presented in the above picture, in the plane perpendicular to directions of the horizontal load is surrounded by piles from one side only and the axial pile spacing equals \( R_{1b} \). There are no adjoining piles on the other side of the corner pile, so its stiffness is limited from one side only. Accordingly the calculation for the \( n_1 \) coefficient for the corner pile No. 3
accounts for greater stiffness. The calculation result is presented as a mean value in accordance with the following formula:

\[
n_{p,\text{pile}3} = \frac{n_1(R_{1b}) + 1.0}{2} = \left(\frac{0.2 \cdot R_{1a}}{D} + 0.4\right) + 1.0 \leq 1.0
\]

In its simplest form the formula for \(n_2\) coefficient equals:

\[
n_2 = \beta + \frac{(1 - \beta) \cdot (R_2 - D)}{1.8 \cdot (D + 0.5)} \leq 1.0 \quad \text{for } D < 1.0m
\]

\[
n_2 = \beta + \frac{(1 - \beta) \cdot (R_2 - D)}{1.8 \cdot (D + 1.0)} \leq 1.0 \quad \text{for } D \geq 1.0m
\]

In the program the calculation of the value of the \(n_2\) coefficient is dependent on the axial spacing of piles that limit the stiffness of the pile – i.e. the piles located in front of the analyzed pile; in accordance with the direction of the horizontal load. As in the example for the corner pile No. 3, for the direction of the horizontal load there is no reduction in stiffness with regard to the axial pile spacing \(R_{2b}\). Therefore the value of the \(n_2\) coefficient for the corner pile No. 3 is exactly the same as for the edge pile No.6 i.e. 1.0.
9. RULES ON CALCULATION OF INTERNAL FORCES AND DISPLACEMENT

Calculations of internal forces can be performed also with or without taking into account soil plastic phenomenon.

It is recommended to perform the calculations of internal forces in piles of foundation with taking into account soil plastic phenomenon, which reflects real co-operation of pile foundation with subsoil. Procedure of calculation for both cases is described below.

9.1 CALCULATION WITH TAKING INTO ACCOUNT SOIL PLASTIC PHENOMENON

The calculations of internal forces with taking into account soil plastic phenomenon are performed iteratively according to the following steps:

1. Initially the co-operation of pile foundation with subsoil is modeling by spring supports arranged along the axis of pile in all nodes.
2. Next horizontal reactions in particular nodes are calculated.
3. Afterward the program checks if the value of horizontal reaction in any node does not exceed the ultimate horizontal soil response. In case of exceeding the ultimate horizontal soil response the program replaces that spring support by concentrated force equals ultimate horizontal soil response and recalculate new static scheme. The exemplary static scheme of pile with taking into account soil plastic phenomenon was presented on picture no. 2a.
4. Steps no. 2 and 3 are executed until the value of horizontal reaction does not exceed ultimate horizontal soil response in all nodes. The final static scheme of pile is estimated iteratively.
5. At last the results of internal forces are presented.

9.2 CALCULATION WITHOUT TAKING INTO ACCOUNT SOIL PLASTIC PHENOMENON

The calculations of internal forces without taking into account soil plastic phenomenon are performed according to the following steps:

1. The co-operation of pile foundation with subsoil is modeling as above by spring supports arranged along the axis of pile in all nodes.
2. Next the horizontal reactions in particular nodes are calculated.
3. Afterward the program checks if the value of horizontal reaction in any node does not exceed the ultimate horizontal soil response.
4. In case of exceed the ultimate horizontal soil response the program shows adequate message but doesn’t change the static scheme of pile.
5. The calculations of internal forces are always made based on the static scheme consisting of spring supports arranged along the axis of pile in all nodes. The exemplary static scheme of pile without taking into account soil plastic phenomenon was presented in the picture no. 2b.

![Static scheme of pile with taking into account soil plastic phenomenon](image1)

**Picture no. 2a**
Static scheme of pile with taking into account soil plastic phenomenon

![Static scheme of pile without taking into account soil plastic phenomenon](image2)

**Picture no. 2b**
Static scheme of pile without taking into account soil plastic phenomenon

### 9.3 CALCULATION OF DISPLACEMENT

Displacement of pile is performed independently of chosen way of calculation the internal forces (i.e. with or without taking into account soil plastic phenomenon).

The value of displacement is always calculated for scheme of pile consisting horizontal spring supports arranged along the axis of pile in all nodes – i.e. according to scheme presented in picture no. 2b.
10. RULES ON CALCULATION OF PILE CORE

10.1. CALCULATION OF CONCRETE PILE CORE

The strain model has been applied for calculating reinforcement and verification load carrying capacity of pile core in ultimate state. The model takes into account non-linear relationship between strain and stress in compression zone. In this model there are the following assumptions:

1. The law of flat sections according to Bernoulli’s principle, which means that the strains of fibres in loaded section are proportional to their distance from the neutral axis.
2. Equality of reinforcing steel strain and surrounding concrete strain at the junction of two materials.
3. Lack of tensile strength of concrete due to cracking of concrete.

The cross-section of pile reaches the ultimate load carrying capacity when at least there is one of the following conditions:

- Strain in tension reinforcement will reach the limit value $\varepsilon_s = -10,0 \%$
- Strain in boundary fiber of compression concrete will reach the limit value $\varepsilon_c = +3,5 \%$
- Strain in the fiber of concrete set 3/7h from more compression edge of section will reach the limit value $\varepsilon_c = +2,0 \%$

The diagram of load carrying capacity of pile core is presented by the program with indication of characteristic values of internal forces in the pile section and the limit values of bending moment and axial force.

10.2. CALCULATION OF STEEL TUBE PILE

The calculation of cross-section of steel tube pile includes checking the normal stress and shear stress. The calculation of normal stresses to which the load acts in a direction perpendicular to the cross-section of pile includes:

- Checking the condition of pile cross-section at bending with compressing – if the axial load of the pile is pull in force;
- Checking the condition of pile cross-section at bending with tensioning – if the axial load of the pile is pull out force.

The calculation of shear stresses to which the load acts in a direction parallel to the cross-section of pile includes checking the condition of pile section at shearing.

If the conditions of load carrying capacity of pile cross-section defined by the user are not fulfilled the program automatically increases thickness of the steel tube pile and displays a message.
11. CALCULATION RESULTS – RESULTS TAB

The results of the performed calculations are shown on scheme of pile foundation. Near each pile of foundation scheme for 4 directions of horizontal load there are displayed values of maximum bending moments within the length of pile.

Details of results for particular piles are displayed after clicking on chosen values of bending moment on the scheme of pile foundation.

In addition, there are presented the summary of results consisting maximum and minimum values of internal forces and displacement for particular piles and directions of horizontal load.

- $M_{\text{max}}$ – maximum value of extreme bending moment along the length of pile
- $M_{\text{min}}$ – minimum value of extreme bending moment along the length of pile
- $T_{\text{max}}$ – maximum value of extreme horizontal force along the length of pile
- $T_{\text{min}}$ – minimum value of extreme horizontal force along the length of pile
- $\delta_{\text{max}}$ – maximum value of pile head displacement
- $\delta_{\text{min}}$ – minimum value of pile head displacement
The following example presents the **way of comparing results** of characteristic piles in scheme of pile foundation with each pile in foundation of bridge pillars.

In the example it was assumed that horizontal load of bridge pillars could effects in two directions parallel to the longitudinal axis of bridge. Depending on head of horizontal load (← or →) to each pile two values of maximum bending moment are applied (117,7 kNm or 141,8 kNm).

As the horizontal load effects alternately for each pile, the final value of maximum bending moment along the length of pile was taken as **141,8 kNm**.

**Picture no. 3.** The way of comparing results of characteristic piles in scheme of pile foundation with each pile in foundation of bridge pillars.
It is worth pointing out that loads in pile head defined by user are identical for each pile in foundation. The difference in results of internal forces and displacement arises from **diversity of ground characteristic** for particular piles.

<table>
<thead>
<tr>
<th>Bending moment in pile</th>
<th>Horizontal force in pile</th>
<th>Pile head displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>M(\text{max}) = 141.8 kNm</td>
<td>T(\text{max}) = 63.5 kN</td>
<td>(\bar{U})(\text{max}) = 20.8 mm</td>
</tr>
<tr>
<td>M(\text{min}) = 117.7 kNm</td>
<td>T(\text{min}) = 62.9 kN</td>
<td>(\bar{U})(\text{min}) = 16.5 mm</td>
</tr>
</tbody>
</table>

The program takes into consideration that for the same type of pile and identical loads in all piles the value of horizontal stiffness of soil \(k_x\) and ultimate horizontal soil response \(R_{gr}\) in designed foundation depend on the following parameters:

- dimension of foundation (amount of rows and column of piles);
- pile location in foundation (corner, edge or inner pile);
- distance between adjoining piles;
- direction of horizontal load.

Nonetheless, the program doesn’t take into account the influence of capping beam for distribution of loads.

### 12. PRESENTATION OF RESULTS OF CALCULATIONS

The detailed presentation of performed calculations is displayed after clicking on particular graphical tabs of results (Soil, Bending moment, Horizontal load, Displacement, Section).
Ground parameters, modulus of soil horizontal stiffness and ultimate soil resistance

Bending moment distribution, horizontal force distribution, pile displacement
Summary table contains results of calculations in particular nodes

Diagram of load carrying capacity of pile core
Pile cross-section with results of steel and concrete

Button **Show calculation details** – displays intermediate parameters of calculation.
Table **Soil parameters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z [m bgl]</td>
<td>ordinate of the soil stratum bottom</td>
</tr>
<tr>
<td>Soil type</td>
<td>type of the soil stratum</td>
</tr>
<tr>
<td>H [m]</td>
<td>thickness of the soil stratum</td>
</tr>
<tr>
<td>ID / IL</td>
<td>soil density index / soil liquidity index</td>
</tr>
<tr>
<td>γ' [kN/m³]</td>
<td>buoyancy unit weight of soil (unit weight of submerged soil)</td>
</tr>
<tr>
<td>φ [°]</td>
<td>friction angle of soil</td>
</tr>
<tr>
<td>δ [°]</td>
<td>pile-soil friction angle</td>
</tr>
<tr>
<td>c [kPa]</td>
<td>cohesion of soil</td>
</tr>
<tr>
<td>E0 [MPa]</td>
<td>initial deformation modulus (Young’s Modulus of soil)</td>
</tr>
<tr>
<td>m1 [-]</td>
<td>corrective coefficient equal 0.7 of cohesive soil and 0.8 of non-cohesive soil</td>
</tr>
</tbody>
</table>

\[
E_0 = \frac{(1 + \nu) \cdot (1 - 2\nu)}{1 - \nu} \cdot M_0
\]

\[
\nu - \text{Poisson’s ratio}
\]

\[
M_0 - \text{oedometer modulus (E_{ed})}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn [-]</td>
<td>coefficient for method of pile embedment</td>
</tr>
<tr>
<td>φ [-]</td>
<td>coefficient for the long-lasting or cyclic loads effect</td>
</tr>
<tr>
<td>Zc [m bgl]</td>
<td>critical height of soil stratum – the thickness of soil stratum when the maximum horizontal soil stiffness is mobilized</td>
</tr>
<tr>
<td>Hz [m bgl]</td>
<td>equivalent height of soil stratum</td>
</tr>
<tr>
<td>Hm [m bgl]</td>
<td>depth of mobilisation the maximum horizontal soil stiffness</td>
</tr>
<tr>
<td>Kx [kPa]</td>
<td>module of horizontal stiffness of soil stratum</td>
</tr>
</tbody>
</table>

Table **Boundary elements and their corresponding Kx values**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z [m bgl]</td>
<td>ordinate of the soil stratum bottom</td>
</tr>
<tr>
<td>Kx_1 [kPa]</td>
<td>module of horizontal stiffness of soil for stratum with bottom on the ordinate Z</td>
</tr>
<tr>
<td>Kx_2 [kPa]</td>
<td>module of horizontal stiffness of soil for stratum with top on the ordinate Z</td>
</tr>
<tr>
<td>A [-]</td>
<td>slope of linear function y=Ax + B</td>
</tr>
<tr>
<td>B [-]</td>
<td>y-intercept of linear function y=Ax + B</td>
</tr>
</tbody>
</table>

Table **Boundary elements and their corresponding Qr values**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z [m bgl]</td>
<td>ordinate of the soil stratum bottom</td>
</tr>
<tr>
<td>σ’v [kPa]</td>
<td>horizontal effective stress in soil</td>
</tr>
<tr>
<td>c_1 [kPa]</td>
<td>cohesion of soil for stratum with bottom on the ordinate Z</td>
</tr>
<tr>
<td>c_2 [kPa]</td>
<td>cohesion of soil for stratum with top on the ordinate Z</td>
</tr>
<tr>
<td>m1 [-]</td>
<td>corrective coefficient for stratum with bottom on the ordinate Z</td>
</tr>
</tbody>
</table>
m2 [-]  – corrective coefficient for stratum with top on the ordinate Z
Sn_1 [-]  – coefficient for the impact of the method of pile embedment for stratum with bottom on the ordinate Z
Sn_2 [-]  – coefficient for the impact of the method of pile embedment for stratum with top on the ordinate Z
Kph’_1 [-]  – coefficient for passive pressure for stratum with bottom on the ordinate Z
Kph’_2 [-]  – coefficient for passive pressure for stratum with top on the ordinate Z
Qr_1 [kPa]  – ultimate horizontal soil resistance for stratum with bottom on the ordinate Z
Qr_2 [kPa]  – ultimate horizontal soil resistance for stratum with top on the ordinate Z
A [-]  – slope of linear function y=Ax + B
B [-]  – y-intercept of linear function y=Ax + B

Table **Kx values in nodes**

<table>
<thead>
<tr>
<th>Z_from [m bgl]</th>
<th>– ordinate of the stratum top</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z_to [m bgl]</td>
<td>– ordinate of the stratum bottom</td>
</tr>
<tr>
<td>Function number</td>
<td>– number of functions defining the module of horizontal stiffness of soil between ordinates Z_from and Z_to</td>
</tr>
<tr>
<td>A1 [-]</td>
<td>– slope of linear function y1=A1x + B1</td>
</tr>
<tr>
<td>B1 [-]</td>
<td>– y-intercept of linear function y1=A1x + B1</td>
</tr>
<tr>
<td>Z2 [m ppt]</td>
<td>– ordinate from which soil stiffness is defined by the second linear function y2= A2x + B2</td>
</tr>
<tr>
<td>A2 [-]</td>
<td>– slope of linear function y2=A2x + B2</td>
</tr>
<tr>
<td>B2 [-]</td>
<td>– y-intercept of linear function y2=A2x + B2</td>
</tr>
<tr>
<td>Z3 [m ppt]</td>
<td>– ordinate from which soil stiffness is defined by the third linear function y3= A3x + B3</td>
</tr>
<tr>
<td>A3 [-]</td>
<td>– slope of linear function y3=A3x + B3</td>
</tr>
<tr>
<td>B3 [-]</td>
<td>– y-intercept of linear function y3=A3x + B3</td>
</tr>
<tr>
<td>Z4 [m ppt]</td>
<td>– ordinate from which soil stiffness is defined by the fourth linear function y4= A4x + B4</td>
</tr>
<tr>
<td>A4 [-]</td>
<td>– slope of linear function y4=A4x + B4</td>
</tr>
<tr>
<td>B4 [-]</td>
<td>– y-intercept of linear function y4=A4x + B4</td>
</tr>
<tr>
<td>Kx [kN/m]</td>
<td>– horizontal stiffness of soil in a node</td>
</tr>
</tbody>
</table>

Table **Rgr values in nodes**

<table>
<thead>
<tr>
<th>Z_from [m bgl]</th>
<th>– ordinate of the stratum roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z_to [m bgl]</td>
<td>– ordinate of the stratum bottom</td>
</tr>
</tbody>
</table>
Function number – number of functions defining the maximum horizontal soil resistance between ordinates Z_from and Z_to

A1 [-] – slope of linear function \( y_1 = A_1 x + B_1 \)

B1 [-] – y-intercept of linear function \( y_1 = A_1 x + B_1 \)

Z2 [m bgl] – ordinate from which soil resistance is defined by the second linear function \( y_2 = A_2 x + B_2 \)

A2 [-] – slope of linear function \( y_2 = A_2 x + B_2 \)

B2 [-] – y-intercept of linear function \( y_2 = A_2 x + B_2 \)

Rgr [kN] – ultimate horizontal soil response in a node

Print results – print results of performed calculations. The program allows printing both graphic and text section of results. It is possible to print results for pile of maximum and minimum bending moment and also for pile selected on the scheme of pile foundation.
Pile bearing capacity – export of data from the program PaleKx to the program PalePN. The current data should be saved into a temporary file, which next will be opened by the program PalePN for calculation pile bearing capacity.

Create soil profile – creates a script (command lines) in the AutoCad. This script is later copied directly to the clipboard. In order to create the soil profile the user needs to run AutoCad, place the cursor on the command line and insert the copied contents (use keys Ctrl + V).