The analysis of influencing factors over the computerised designing process of deep excavations near roads in urban environment

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Abstract. The article aims to show the errors that a user can make in the use of inappropriate computing programs for the calculation of support structures and / or inadequate use of geotechnical data when designing support for deep excavations near roads in urban areas, and to indicate the software that offers plausible and reality-related results. Comparisons were made between the displacements and the efforts of ground support elements from numerical computational models in which was varied the coefficient of bedding for horizontal actions and between geotechnical calculation models.

1. Introduction
Design solutions for geotechnical road support structures are currently based on simplified numerical experience and calculations. Three-dimensional numerical modeling is not commonly used due to the lack of codes for proper and correct interpretation of the results obtained from the Finite Element Methods calculations.

2. Material and Methods
Retaining walls are inherently retaining soil structures, i.e. providing lateral support with sufficient moment capacity to resist the action of lateral load from soil pushing. In contrast, piles are traditionally single structures with the ability to resist axial loads. In practice, this black or white approach is not feasible and piles are often relied on to resist lateral loads [1].

In the following chapter, we will present the theoretical bases on modelling the interaction of interspaced pile land-support structures near roads in urban areas.

A particular problem is the correct choice of the available and realistic constitutive models to describe as accurately the behavior of the foundation ground as the task.

A mandatory condition for correctly using soil behavior patterns in the Finite Element program is the use of geotechnical parameters (cohesion, internal friction angle, stiffness, etc.) obtained from in-situ or laboratory tests. In order to assess the efforts and the state of tension in the support structures, the numerical modeling of the supporting structure, the foundation ground and the supported ground as well as the cooperation between the support structure and the ground should be as close as possible to the reality.
At present, the spatial computing programs commonly used for calculating road support structures in our country are Plaxis 3D and AxisVM.

Numerical calculations of buildings and structures in the framework of soil-structure interaction do not pertain only to the domain of design of unique and technically sophisticated or hazardous buildings and structures any more.

They become actively involved in everyday design practice which, as a rule, includes geotechnical investigations [2, 3].

2.1. Plaxis 3D Program

The results obtained from spatial calculations with the PLAXIS - 3D Foundation Program are in the form of displacements, efforts, internal forces, moments and, in particular, failure of the support (tension and cracks) and the ground, results that allow the designer to create a close vision the reality of the projected support risk.

Numerical modelling of the program - The mechanical behavior of the terrain used for the calculations in this paper is elastic-plastic behavior Mohr-Coulomb Model.

The Mohr-Coulomb Model - This constitutive model implies 5 characteristic parameters: ground stiffness - $E$ and Poisson coefficient $\nu$ for the elasticity part as well as $\phi$, $c$, dilatandcey angle $\psi$ to model the plasticity of the terrain.

The "embedded pile" used for the calculation of support structures, is a pile made up of bar elements that can be placed in random direction in the soil and which interacts with the perimeter soil through special interface elements.

This interaction may involve a base resistance besides a mantle resistance. Although an embedded pile does not occupy a volume, the program considers around the pile a particular volume depending on the pilot diameter (elastic area) excluding the plastic behavior of the soil. The basic parameters include the rigidity of the pilot, the unit weight of the material in the pile $\gamma$, geometric cross-sectional parameters, mantle resistance and base resistance.

2.2. Axis VM Program

The program is a static and sizing program based on the finite element method used predominantly for the constructions superstructure calculation.

For the calculation of an earth support structure in Axis VM, according to the calculation methods from geotechnical norms and specialty literature it can be considered in the calculation the beam Theory on Winkler elastic environment of a pile supposed to transversal loadings.

According to the calculation model in the book "Geotechnical Engineering Applications" [4] there is the following numerical calculation method: the ground on the plug $f$ is considered to be on a Winkler elastic environment characterized by the horizontal displacements bed coefficient $k_h$ and by the vertical displacements bed coefficient $k_v$.

The $k_h$ coefficient increases linearly with the depth after the relation $k_h = mz$, $m$ being the proportionality coefficient from table 1.

If a bar is placed vertically in this environment and it is loaded with a horizontal force (figure 1), at a depth $z$ it will record a horizontal pressure $\sigma_h(z)$. According to Winkler Hypothesis, this pressure is proportional to the displacement following the relation:

$$\sigma_h(z) = k_h \gamma(z)$$

From a physical point of view, the Winkler environment is made up of elastic arches arranged between the bar and a rigid base.

According to the relation (1), the bed coefficient $k_h$ is the horizontal pressure appearing in a section if the displacement in that section is equal to 1. Dividing the plug $f$ embedding section into segments of length $a$, and the continuous bearing between the bar and the ground is replaced by springs in the centers of these segments.
The punctual support is achieved by means of elastic arcs between the bar and the rigid base. Since the bar is also supported vertically on the ground, an arc is also inserted in this direction at the bottom end of the bar, figure 2.

When the element deforms under the action of earth pushing, elastic reactions occur in the arches. The elastic reaction in the horizontal arc $i$ is:

$$R_{xi} = mz_ia_y$$

Considering the terrain bedding coefficient for each vertical displacement $k_v$ equal to the horizontal bed coefficient from the depth $f$ ($k_v = mf$), the elastic reaction in the vertical spring is:

$$R_{vi} = mfAz_v$$

Considering $A$ the area of the cross sections of the earth supporting structure, $z_v$ is the vertical movement of the wall; $b$ is the width of the earth-supporting wall element.
The value $m_{z_{i_{ab}}}$ from relation (2) represents the reaction from the point $i$ if the displacement $y_i = 1$, meaning the rigidity of the elastic bearing in $i$. Similarly, $m_{fA}$ from relation (3) is the rigidity of the vertical elastic spring.

These rigidities must be entered into the calculation program along with the other input data. The calculation program will give the values of the displacements, reactions and sectional stresses ($N, M$ and $Q$) at all points $i$ selected on the wall.

From the reactions, the horizontal pressure $\sigma_h$ between the wall and the earth is obtained: $\sigma_h = \frac{R_{ei}}{(ab)}$, which can be calculated with the relation (1).

The maximum value of this pressure must be less than the horizontal load bearing capacity ($CP_h$), which can be calculated with the relation:

$$CP_h = 2(\gamma z t g \phi + c)$$

in which $\gamma$, $\phi$, $c$ are the ground characteristics of the plug $f$.

Since the load capacity varies with the $z$ depth, the check $\sigma_h(z) \leq CP_h$ will be done both for the maximum positive pressure and its negative maximum value. If the check is not satisfied, the plug in the soil $f$ is insufficient.

Considering the result of the $\sigma_h(z)$ diagram is equal to the result of applied load, by increasing the plug the ordinates of the diagram will decrease, and the verification will be fulfilled.

**Table 1.** Coefficient of proportionality $m$—(Table C.1 [8]).

| Soil type                                | Coefficient $m$ [kN/m²] |
|------------------------------------------|--------------------------|
| Prefabricated piles | On site executed piles |
| Clays and silty clays with $I_c \leq 0.25$ | 650-2500 | 500-2000 |
| Clays and silty clays with $I_c = 0.25 - 0.50$, sandy silts with $I_c \leq 1.00$ and silty sands with $e = 0.6-0.8$ | 2500-5000 | 2000-4000 |
| Clays and silty clays with $I_c = 0.50 - 1.00$, sandy silts with $I_c > 1.00$ and fine and medium sands | 5000-8000 | 4000-6000 |
| Clays and silty clays with $I_c > 1.00$ and big sands | 8000-13000 | 6000-10000 |
| Sand with gravel, gravel and cobble sand | - | 10000-20000 |

2.3. **Input data of computing programs used**

In this paper were used, for the two programs, the following partial factors for Design Approach 1 – Group 2:

- Partial factors for permanent and variable unfavorable actions (A2): $\gamma_{G,unf} = 1.00$, $\gamma_{Q,unf} = 1.30$.
- Partial factors for soil parameters (M2): $\gamma_\phi = 1.25$ for internal friction angle, $\gamma_c = 1.25$ for cohesion and $\gamma_\gamma = 1.00$ for volumetric weight.

It is considered that there is no hydrostatic level. There is a 5 kN/m² surcharge load from the road. The actions, the effect of the actions as well as the geotechnical properties of the stratification are the same for the two programs used in this paper.

The soil layers considered are shown in figure 3 below.
2.3.1. Inputs for Plaxis 3D. Ground characteristics: The design values of soil rigidity by module of elasticity (E), Poisson coefficient (υ), internal friction angle (φ), cohesion (c), are the input data for the soil layers and are presented in the table 2 below.

Table 2. Geotechnical input data for the soil layers.

| Layer | Upper elevation | Lower elevation | Thickness | Design approach 1 – Group 2 |
|-------|----------------|----------------|-----------|-----------------------------|
|       | m m m | kN/m² | kPa | kN/m³ | υ |
| 1. Fillings | 0.00 1.80 | 1.80 | 5.0E+3 | 34.82 | 5.00 | 19.00 | 0.30 |
| 2. Mixed powdery clay + clayey powder | 1.80 2.80 | 1.00 | 1.0E+4 | 19.18 | 22.00 | 19.40 | 0.35 |
| 3. Fine sand | 2.80 3.50 | 0.70 | 9.0E+3 | 24.79 | 5.00 | 19.50 | 0.30 |
| 4. Mixed clay + powdery clay | 3.50 8.70 | 5.20 | 2.5E+4 | 14.57 | 20.00 | 20.85 | 0.35 |
| 5. Hard clay | 8.70 20.00 | 3.00 | 2.9E+4 | 7.02 | 50.00 | 21.18 | 0.42 |

Pile characteristics are: elastic modulus for C25/30 concrete E = 3.15E+07 kN/m²; volumetric mass of the concrete in the pile γ = 25 kN/m³.

The skin resistance and base resistance are inputs evaluated according NP 123-2010 [5] or according with results from displacement measurements on site.
The active pushing and bed coefficients for the embedded plug are automatically calculated by the program, representing output data.

2.3.2. Inputs for Axis VM. Ground characteristics: The active pushing are calculated according to [9] and the horizontal load bed coefficients are quantified by the proportionality coefficient. The active pushing and the horizontal bed coefficients are the input data, so, if not correctly approximated, the results are not realistic.

The active pushing’s design values have been synthesized in the table 3 below for Design Approach 1 - Group 2 because the results are the most unfavorable states of effort [7] for the case treated in the paper.

| Layer | Upper elevation m | Lower elevation m | Thickness m | Design approach 1 – Group 2 |
|-------|------------------|-------------------|-------------|-----------------------------|
| 1. Fillings | 0.00 | 1.80 | 1.80 | 0.03 | 34.82 | 5.00 | 19.00 | 1.10 |
| 2. Mixed podery clay+clayey powder | 1.80 | 2.80 | 1.00 | 0.23 | 19.18 | 22.00 | 19.40 | 12.72 |
| 3. Fine sand | 2.80 | 3.50 | 0.70 | 0.14 | 24.79 | 5.00 | 19.50 | 9.25 |
| 4. Mixed clay+powdery clay | 3.50 | 8.70 | 5.20 | 0.35 | 14.57 | 20.00 | 20.85 | 39.09 |
| 5. Hard clay | 8.70 | 20.00 | 3.00 | 0.61 | 7.02 | 50.00 | 21.18 | 72.98 |

Pile characteristics are: elastic modulus for C25/30 concrete E = 3.15E+07 kN/m², volumetric mass of the concrete in the pile γ = 25 kN/m³.

According to the Winkler Approach, the coefficient of bedding for horizontal displacements increases linearly with the depth after the expression k_h = mz, where m is the proportionality coefficient [kN/m⁴], table 1, depending on the nature of the soil (cohesive, non-cohesive), physical and mechanical characteristics of the soil, of the pile type (prefabricated, executed on the spot); z - the depth of excavation

The active pushing and bed coefficients for the embedded plug represents input data.

3. Results of modelling an earth support structure near urban road in non-specialized geotechnical program

In this chapter we present the calculation of a road support structure made of 40 cm diameter piles with interspaces at 70 cm between the axes, with a depth of excavation of 8.70 m and a plug length of 4.00 m in Axis VM, a non-geotechnical program.

With the geotechnical data taken from table 4, several calculation models were made:
- (a) variation of the bed coefficient k_s for vertical loads in the case of a similar length pile embedding with and high consistency index - inadequate modelling; The values of the coefficient of bed k_s will be taken from table 4 below, according to norm NP 112-2014 [6], table K.2, for a clayey soil:

| Table 4. Bed coefficient values k_s [4]. |
|----------------------------------------|
| The vertical bed coefficient in correlation with consistency index for clayey soils |
| Plastic flowing soil | Soft plastic soil | Consistent plastic soil | Plastic strong soil |
| I_c | 0÷0.25 | 0.25÷0.50 | 0.50÷0.75 | 0.75÷1.00 |
| k_s | - | 7000÷34000 | 34000÷63000 | 63000÷100000 |

- (b) variation of the bed coefficient for horizontal loads k_h by means of the coefficient of proportionality m [kN/m⁴] in the case of a pile embedding with a low, medium and high consistency
index for a clayey soil - accepted modelling for pre-dimensioning. The values of the proportional coefficient \( m \) will be taken from table 1 [3, 8].

The calculations models performed whom taken into account the proportionality coefficient \( m \) [kN/m^4] with the maximum value for clayey soil will be compared to the calculation model made by calibrating the geotechnical data of the constitutive model in the Plaxis 3D program.

3.1. Inadequate modeling – the use of the vertical loads bedding coefficient \( k_s \)
According to above point 3(a), in the following figure 4 we present the results consisting in charts of efforts and horizontal displacements for the variation of the coefficient of bed for vertical loads \( k_s \) used for horizontal loads from low values of 63000 kN/m^3 to maximum values of 100000 kN/m^3 on the considered high consistency index with similar length clay embedding.

![Vertical Bedding coefficient \( k_s \)](image)

| Value   | \([\text{kN/m}^3]\) | \(M_{\text{max}}\) [kNm] | \(Q_{\text{max}}\) [kN] | \(e_x\) [mm] |
|---------|-------------------|---------------------|-----------------|-----------|
| Minim   | 63000             | 289                 | 145             | 189       |
| Middle  | 81500             | 289                 | 160             | 182       |
| Maxim   | 100000            | 289                 | 173             | 178       |

**Figure 4.** Charts for: (a) Bending moment; (b) Shear force; (c) Horizontal displacements.

3.2. Acceptable modeling - Bed coefficient variation for horizontal displacements \( k_h \) (horizontal loads)
According to above point 3. (b), in the following figure 5 are synthesized the results consisting in charts of efforts and horizontal displacements for the variation of the coefficient of horizontal soil reaction \( k_h \) from the low values of 6000 kN/m^4 to the maximum values of 10000 kN/m^4 on the considered high consistency index with similar length clay embedding.
4. Results of a site executed earth support structure near an urban road

Based on the topographic survey carried out on site in the analysed area and the geotechnical design values

4.1. Accepted modeling - Bed coefficient variation for horizontal displacements \( k_h \) (horizontal loads) - modeling performed with Axis VM

The following figure 6 presents the results calculation of a earth retaining wall near urban road made of piles with 40 cm diameter, with interspaces at 70 cm between axes, with a maximum excavation depth of 8.70 m and a ground embedding length of 4.00 m.

The coefficient \( k_h \) was used depending on the characteristics of the soil in which the piles are embedded for maximum values of 10000 kN/m³.
4.2. Optimal modeling - geotechnical data calibration with topometric measurements

The following figure 7 presents the results calculation of an earth retaining wall near urban road made of reinforced concrete piles with 40 cm diameter, with interspaces at 70 cm between axes, with a maximum excavation depth of 8.70 m and a ground embedding length of 4.00 m after a model calibration according to in-situ measurements of the piles displacements.

(a) Bending moments diagram
\[ M_{\text{min}} = -107 \quad M_{\text{max}} = 41 \]

(b) Shear forces diagram
\[ Q_{\text{min}} = -87 \quad Q_{\text{max}} = +110 \]

(c) Horizontal displacements diagram
\[ u_{\text{sup}} = 253 \quad u_{\text{inf}} = 22 \]

Figure 7. Charts for: (a) Bending moment; (b) Shear force; (c) Horizontal displacements.

4.3. Situation with half pile length embedding

Given that the depth of excavation is more than 8.00 m and the pile diameter is only 40 cm, it presents high rotations and displacements, therefore in the following it will be presented the comparative results of the 40 cm diameter and of 80 cm diameter with half-length embedding calculations for the earth supporting wall, executed near urban road, made with Axis Vm and the calculations performed in Plaxis 3D.

4.3.1. Axis VM – Reinforced concrete piles, \( L=16.70 \) m (excavation 8.70 m – embedded 8.00 m), \( D=40 \) cm. The following figure 8 presents the results calculation of an earth retaining wall made of reinforced concrete piles with 40 cm diameter, with interspaces at 70 cm between axes, with a maximum excavation depth of 8.70 m and a ground embedding length of 8.00 m after a model calibration according to in-situ measurements of the piles displacements.

It can be noted that the movement recorded at the free end is very high and that on the embedding length, the pile has buckling characteristics.

(a) Bending moment diagram
\[ M_{\text{max}} = 341 \text{ kNm} \]

(b) Shear force diagram
\[ Q_{\text{max}} = 132.36 \text{ kN} \]

(c) Horizontal displacements diagram
\[ e_{\text{x}} = 345 \text{ mm} \]

Figure 8. Charts of efforts for: (a) Bending moment; (b) Shear force; (c) Horizontal displacements.
4.3.2. Axis VM - Reinforced concrete piles, \( L=16.70 \, m \) (excavation \( 8.70 \, m \) – embedded \( 8.00 \, m \)), \( D=80 \, cm \). The following figure 9 presents the results calculation of an earth retaining wall, near an urban road, made of reinforced concrete piles with 80 cm diameter, with interspaces at 110 cm between axes, with a maximum excavation depth of 8.70 m and a ground embedding length of 8.00 m after a model calibration according to in-situ measurements of the piles displacements. It can be noted that the displacement at the free end and the rotation is reduced by about 90% compared to the 40 cm diameter pile showed at previous point and that the moment diagram only appears on the active pushing side.

\[
\text{Model} \quad \begin{array}{ccc}
(a) \text{Bending moment} & (b) \text{Shear force} & (c) \text{Horizontal displacements} \\
\text{diagram} & \text{diagram} & \text{diagram}
\end{array}
\]

\[
M_{\text{max}} = 398 \, \text{kNm} \quad Q_{\text{max}} = 94 \, \text{kN} \quad e_x = 41.86 \, \text{mm}
\]

**Figure 9.** Charts for: (a) Bending moment; (b) Shear force; (c) Horizontal displacements.

4.3.3. Plaxis 3D - Reinforced concrete piles, \( L=16.70 \, m \) (excavation \( 8.70 \, m \) – embedded \( 8.00 \, m \)), \( D=40 \, cm \). The following figure 10 presents the results calculation of a earth retaining wall, near an urban road, made of reinforced concrete piles with 40 cm diameter, with interspaces at 70 cm between axes, with a maximum excavation depth of 8.70 m and a ground embedding length of 8.00 m after a model calibration according to in-situ measurements of the piles displacements.

It can be noted, compared to Axis calculations for the same situation (see point 4.3.1) that the displacement and the internal forces are much smaller.

\[
\text{Model} \quad \begin{array}{ccc}
(a) \text{Bending moment} & (b) \text{Shear force} & (c) \text{Horizontal displacements} \\
\text{diagram} & \text{diagram} & \text{diagram}
\end{array}
\]

\[
M_{\text{min}} = -76 \quad M_{\text{max}} = 33 \\
Q_{\text{min}} = -78 \quad Q_{\text{max}} = +44 \\
u_{\text{xmax}} = 79 \quad u_{\text{min}} = 19
\]

**Figure 10.** Charts for: (a) Bending moment; (b) Shear force; (c) Horizontal displacements.
4.3.4. Plaxis 3D - Reinforced concrete piles, \(L=16.70\ m\) (excavation \(8.70\ m\) – embedded \(8.00\ m\)), \(D=80\ cm\). The following figure 11 presents the results calculation of an earth retaining wall, near an urban road, made of reinforced concrete piles with 80 cm diameter, with interspaces at 110 cm between axes, with a maximum excavation depth of 8.70 m and a ground embedding length of 8.00 m after a model calibration according to in-situ measurements of the piles displacements. It can be noted, compared to Axis calculations for the same situation (see point 4.3.2) that the displacement at the free end is higher, but the value of the moments is reduced by 25%.

| Model | Bending moment [kN\(\text{m}\)] | Shear force [kN] | Horizontal displacements [mm] |
|-------|---------------------------------|------------------|-------------------------------|
|       | \(M_{\text{min}} = -248\ kN\text{m}\) | \(Q_{\text{min}} = -58\ kN\) | \(u_{x\text{sup}} = 69\ mm\) |
|       | \(M_{\text{max}} = -200\ kN\text{m}\) | \(Q_{\text{max}} = +64\ kN\) | \(u_{x\text{inf}} = 21\ mm\) |

Figure 11. Charts for: (a) Bending moment; (b) Shear force; (c) Horizontal displacements.

5. Discussions – Errors made at data input
Incorrect linear estimation of the bed coefficient, given the spatial behaviour (3D) of the state of effort in the pile surrounding soil. Also the coefficient of bedding for vertical loads in the geotechnical literature is estimated by tests with rectangular and not circular surfaces, as is the case of a circular pile from an earth supporting structure for a deep excavation in an urban area.

Some programs allow the choice of geotechnical parameters but not all users have sufficient knowledge to correctly approximate these geotechnical parameters. The most common mistake is that the calculations of an earth supporting structure near an urban road in computer programs is made by non-specialist engineers in geotechnics. The main error in introducing data into programs, used just for structural calculation, is the inadequate calculation of the springs rigidity for the Winkler approach, by confusing the coefficient of bedding from tabs 8.1 and 8.2 of NP 112-2014 [4] \(k_s [\text{kN/m}^3]\) for vertical loads on the soil with the coefficient of proportionality \(m [\text{kN/m}^4]\) [4, 6, 8], for horizontal actions on the soil. This leads to erroneous results (less displacements and less efforts versus reality) and hence to the geotechnical failure of the piles after the excavation, figure 12.

Figure 12. Pile spin and measured top displacement of 26 cm.
There are also cases where the coefficient of bedding was considered constant on the embedded depth, although according to the literature, the bed coefficient transformed into the proportionality coefficient varies linearly with the depth.

The calculations in the two programs are made without considering a piezometric line.

It was considered, as shown in figure 12 above that the soil does not flow among the piles.

6. Conclusions

6.1. Comparison between pilot diameters

The moment diagram changes its character: in the case of the 40 cm diameter pile, the stretched concrete fibre appears also on the active pushing side.

The bending moment value of the $D = 40$ cm to $D = 80$ cm is increased by 10 % in the Axis program and by more than 50 % in the Plaxis program.

For the considered situation, in the Axis program the rotation is lower when using piles with diameter of 80 cm; the value is reduced by about 90 %;

The upper displacement is about 88 % lower for the piles with a diameter of 80 cm.

The value of the shear forces in the concrete element decreases with the diameter of the pile.

6.2. Comparison of the computing programs

There are specialized programs for support elements, but for any pre-dimensioning and a primordial cost estimation, any structural calculation program that accepts elastic supports can be used only if the provided input for sensible estimated geotechnical parameters are as possible as accurate.

In subsequent design and execution phases, when it is necessary to determine the reinforcing and the displacement of the earth outside the excavation, only specialized geotechnical engineering programs will be used.

It is imperative to model earth supporting structures for deep excavations in urban areas with an 3D program to take into account corner areas of the supports.

For the estimation of the rigidity of springs for the horizontal reaction of the soil, the tables for the proportionality coefficient $m$ (kN/m³) [3, 6] shall be used and not the value of the coefficient of bed $k_s$ (kN/m³) [4], which is approximately 10 times higher, thus leading to less effort and displacements in earth supporting deep excavation walls made from piles cast on site than real displacements.
Although the Winkler model admits the hypothesis of using a bed coefficient for horizontal displacements, in reality the displacement of a point from the support structure - perimeter soil interface has at least two components: horizontal and vertical, so, it is preferably to model a support structure in a special 3D Geotechnical program.

Also, according to NP 113-2004 [7], the use of the finite element method that are at the base of the geotechnical programs is considered to be a method that offers complete theoretical solutions. The necessary incorporation depth of the wall is generally determined from the required slide stability [10]. The slide stability is defined in such a way that the total of the stimulated laying forces at the foot of the wall is compared with the total of the possible passive soil pressure [11].

The existing modern software complexes making numerical calculations do not always consider these particularities. Moreover, commercial software largely used in the global practice of construction design not always can confirm data obtained at real sites concerning actual strain-stress behaviour of buildings and structures. In a number of cases, software becomes a "black box", whereas a geotechnical engineer involved in calculations is not able to be an active participant of simulation. Application of soil models which are not tested and adapted to geotechnical conditions of a certain area is a factor of excessive risk for high-level responsibility of structures [12].

For deep excavations support in urban areas, for obtaining small effective displacements, it is recommended to use piles with a minimum diameter of 80 cm with a sufficient embedding length.

### 6.3. Influence of increasing pile diameter and depth of embedding

The calculations presented above shows, for the calculation comparison of 40 cm pile to the 80 cm diameter pile, that the horizontal displacements decrease by an approximate 1.00 cm, the shear forces also decrease by an approximate 10% and the character of the bending moments is changed.

Compared with Axis VM modelling, in the 3D Plaxis modelling for larger diameter piles and half-length embedding, it is found that the moments and the shear forces in the piles of an earth support element for a deep excavation in urban areas are smaller, but the displacements are at least 25 % bigger.

**Table 6. The variation of efforts values with the increase of embedding length.**

| Computer program | Embedding length for 80 cm diameter piles | Bending moment [kNm] | Shear force [kN] | Displacements [mm] | Variation of displacement values |
|------------------|------------------------------------------|-----------------------|------------------|-------------------|-------------------------------|
| Axis             | 4 m                                      | 289                   | 173              | 178               |                               |
| Plaxis           | 4 m                                      | 107                   | 110              | 253               | +25%                          |
| Axis             | 8 m                                      | 398                   | 94               | 54                |                               |
| Plaxis           | 8 m                                      | 248                   | 58               | 69                | +27%                          |

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