EMIB Energy & Materials in Infrastructure & Buildings University of Antwerp

Benchmarking of single pile foundations, comparing Eurocode 7 with software programs

K. Dierckx [1], J. Blom [1] and M. Ghalandari [1]

[1] Faculty of Applied Engineering, University of Antwerp
Groenenborgerlaan 171, 2020 Antwerp, Belgium

Contact : kristof.dierckx2@student.uantwerpen.be

Abstract: This paper investigates the design of pile foundations for conventional buildings. However, there are several methods to design pile foundations, which leads to confusion and different outcomes. This problem is due to the soil parameters within geotechnics. This is solved in different analytical calculation models (i.e. Eurocode 7 and Smith's) and with the commercial software programs (i.e. *Deltares* and *Geo5*). Despite the fact that Eurocode 7 is the legislation for designing pile foundations, the results of other calculation methods are disseminated. First, the results are analyzed by conducting a parameter study. Subsequently, the differences are examined by decomposing the calculation formulas. Finally, a short study is performed on what would happen if a homogeneous soil transitions into two layers. The acquired result shows that there are differences between the calculation methods. When working with ground parameters, the analytical method by Eurocode 7 tends to be the most conservative. On the other hand, in the cone resistance value-based design, *Deltares* provides the most conservative output results.

Keywords: Pile foundation; bearing capacity; Eurocode 7; Deltares; GEO5; Smith's;

1. Introduction

Recently, there has been an increase in the construction of high-rise buildings with a large design load on the ground with an insufficient bearing capacity, which creates a necessity for using deep foundations. A pile foundation is a deep foundation since pile foundations transfer the load to a deep located bearing layer. This is useful when the higher located layers have no or little bearing capacity. The standard procedures for designing pile foundations have been worked out in the Eurocode, which is considered to be the legislation. The Eurocode demonstrates how pile foundations are designed using benchmark exercises. Moreover, it explains what methods can be used and establishes boundary conditions, regarding the design [1].

It is of interest to compare the acquired results from the Eurocode with other calculation methods. For this thesis, two software programs are used, namely *Geo5* and *Deltares*. These software programs claim to be in compliance with the legislation. However, it is questionable if this claim is trustworthy. Another analytical calculation method, apart from the Eurocode, is used for this comparison as well, which is described in Smith's book, by Ian Smith [2].

The aim of the present paper is to identify the differences between the legislation and the other calculation methods. Thus, the main research question is: *'What are the differences between Eurocode 7 and other calculation methods, for designing pile foundations?'*. The findings show that the results are different in several cases. In the following chapters of the paper, we will discuss the theoretical base for designing pile foundations together with the research design. Subsequently, the results are discussed and the main research question is answered within the framework of the conclusion. Lastly, a short addendum is given, where three foundation types, namely strip foundations, plate foundations, and pile foundations are compared to each other when calculated in different programs. This addendum is a cooperation between two other final projects and can be found in appendix A.

2. Theoretical base

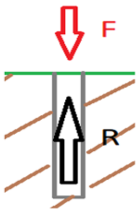
This section briefly discusses the existing literature, followed by the terminology and the state of the art.

2.1. *Literature review*

This literature review contains three different approaches that are used for designing pile foundations. These approaches can be classified as deterministic, probabilistic, and semi-probabilistic methods, each with its philosophy to satisfy the safety of the structure. Evidently, to acquire this safety, the design load must be smaller than the design resistance [3].

2.1.1. Deterministic method

The deterministic method is a system in which no randomness is involved. With a given starting condition or initial state, it will always result in the same output. In this method, safety is introduced with a global safety coefficient S, shown in Figure 2.1, in order to compensate for all uncertainties involved in the design [3].



$$F_d = F_k \quad (1)$$

$$R_d = {R_k}/{S} \quad (2)$$

Figure 2.1: Deterministic method

2.1.2. Probabilistic method

The probabilistic method is a system that assumes a small probability of failure that is acceptable, shown in Figure 2.2. In this method, a statistical analysis is executed in which each variable is a probability distribution. The probabilistic design predicts the flow of variability, which the designer can use to reduce the flow of random variation and improve quality. However, this method requires plenty of data and processing power [3, 4].

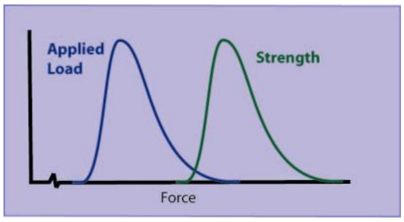
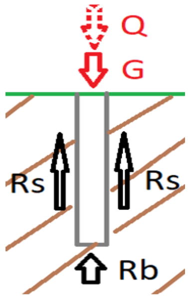


Figure 2.2: Probabilistic method, example [4]

2.1.3. Semi-probabilistic method

Between the probabilistic and deterministic methods, we distinguish the semi-probabilistic method. In this method, safety is introduced with partial safety coefficients, which apply to the actions, soil parameters, and resistances. The safety coefficients depend on the used design approach [3].



$$F_d = G * \gamma_G + Q * \gamma_Q \quad (3)$$

$$R_d = \frac{R_{b,k}}{\gamma_b} + \frac{R_{s,k}}{\gamma_s} \quad (4)$$

Figure 2.3: Semi-probabilistic method, with safety coefficients applied to action (Eq.3) and resistances (Eq.4)

The design approach that is used depends on the national annex, in particular in Belgium design approach 1, combination 1 and 2 are used. Combination 1 focuses on safety against unfavorable load deviations, while combination 2 focuses on safety against unfavorable deviations of the resistance. For pile foundations in Belgium, design approach 1 combination 2 is normative, where the combination of partial factor values is as follows [5, 6]:

$$DA1.C2: A2 + M1 + R4$$

2.2. *Terminology*

Currently, the deterministic method is used to control calculations and as a quick preliminary design method. The probabilistic method is more suited for large projects, while the semi-probabilistic method is ideal for conventional buildings, which is the main target of this study.

The semi-probabilistic method forms the backbone of safety throughout all the

Eurocodes. There are 10 Eurocodes each containing information about their field of interest, shown in Table 2-1. For this study, Eurocode 7 is consulted, which uses Meyerhof's equation (1951) [5].

Table 2-1: Eurocodes and their fields of interest [5]

Eurocode: Basis of structural design	(EN 1990)
Eurocode 1: Actions on structures	(EN 1991)
Eurocode 2: Design of concrete structures	(EN 1992)
Eurocode 3: Design of steel structures	(EN 1993)
Eurocode 4: Design of composite steel and concrete structures	(EN 1994)
Eurocode 5: Design of timber structures	(EN 1995)
Eurocode 6: Design of masonry structures	(EN 1996)
Eurocode 7: Geotechnical design	(EN 1997)
Eurocode 8: Design of structures for earthquake resistance	(EN 1998)
Eurocode 9: Design of aluminium structures	(EN 1999)

The software programs, *Deltares* and *Geo5*, are developed accordingly to Eurocode 7. *Deltares* is a knowledge institute that focuses on water and geotechnics. The institute released several individual software programs [7]. *Geo5* is a structural engineering software that can be divided into several individual programs, in which each program analyses a definite structure type. For this thesis, the programs, *D-Foundations*, by *Deltares*, and *Pile*, and *Pile CPT* by *Geo5* are utilised [8]. In *Deltares* the safety factors have to be overruled, while in *Geo5* they have to be inserted manually because the software program always uses combination 1 for design approach 1.

For *D-Foundations* and *Pile CPT* a CPT profile must be inserted, while in the *Pile* program, ground parameters need to be inserted. In this program three different calculation methods exist to calculate the bearing capacity in drained conditions [9]:

1. NAVFAC DM 7.2: uses a similar calculation method as the Eurocode, however, it is a publication from the U.S. Department of the Navy.
2. Effective stress: has a different calculation approach than the Eurocode and uses effective stress, instead of the cohesion.
3. CSN 73 1002: is a Czech standard in which this method carries out the calculation, accordingly to this standard, while other coefficients are not used.

The fourth calculation method described by Ian Smith in Smith's book, Elements of Soil Mechanics is based on Meyerhof's equation (1951), it has a similar approach as Eurocode 7 but does not apply any correlation factors [2]. This method will be referred to as: 'Smith's method' in this paper.

2.3. *State of the art*

In Belgium, two sources of theory are used for determining the bearing capacity of a pile. First of all, Meyerhof is used when ground parameters are known, while De Beer is used when a cone penetration test is performed. However, these calculation rules can never be an exact prediction of the load-bearing capacity, due to a deviation between the predicted and the real value [2, 3].

The equation of Meyerhof (1951) is used to obtain the equations for the base and shaft resistance of a pile. The problem of Meyerhof can be found within the bearing capacity factors. Scientists, such as Berezantzev, Meyerhof, Vésic, and Hansen, conducted research into these factors, however different results were obtained [2].

The theory by De Beer is used to obtain the base and shaft resistance of a pile as well. De Beer himself is the founder of Belgian soil mechanics, and his theory is widely used in Belgium [3].

3. Research design

In this chapter, we discuss the problem, the procedure, the dataset and the limitations used to achieve the obtained results.

3.1. *Model*

Before starting with any calculations, a model has to be defined. For this problem, a simple model is used with homogenous soil, a single pile, and a centric load acting at the top of the pile.

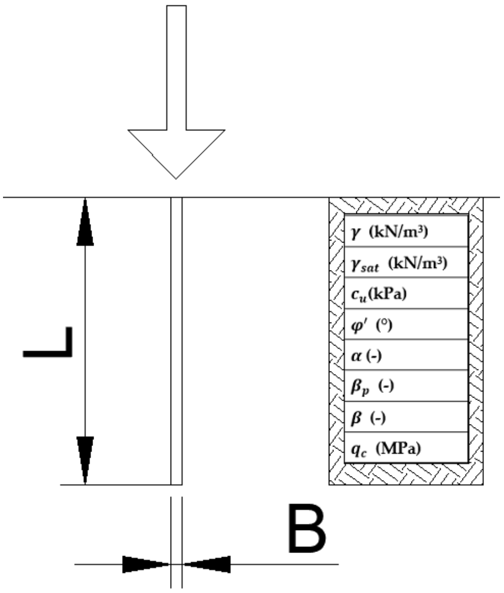


Figure 3.1: Calculation model

3.2. Procedure

In this study, the bearing capacity of a single pile that is subjected to compression is calculated using analytical calculation methods (i.e. Smith's and Eurocode 7) and software programs (i.e. *Geo5* and *Deltares*). This calculation is conducted using the model given in, Figure 3.1.

Now a parameter study is applied to each calculation method for a cohesive and cohesionless soil type, because their calculation methods are different. Moreover, there are two calculation methods when ground parameters are known from either a cone penetration test (CPT) or a standard penetration test (SPT), resulting in four parameter studies:

Table 3-1: Conducted parameter studies

	SPT	**CPT**
Cohesive soil	SPT-Cohesive	CPT-Cohesive
Cohesionless soil	SPT-Cohesionless	CPT-Cohesionless

In each case study, shown in Table 3-2, the influencing factors are modified, within a specific range, to reflect their influence on the bearing capacity. Each calculation method within each parameter study is then compared to each other, by plotting it in graphs.

Following, an additional calculation is conducted to investigate what happens when a homogenous soil transitions into a two-layered soil. This is conducted by using a similar soil type with weaker or stronger ground parameters. This soil replaces, in steps of one meter, the original soil until a specific depth, when no more influence on the bearing capacity is noticed. This will conclude the research procedure of this study.

The sub-category, SPT-Cohesionless, will not be discussed as no benchmark exercise has been issued by Eurocode 7. A different source was consulted, but due to the fact that this source uses no safety factors and no correlation factors, suspicion arose. After performing the calculation and comparing these to the other parameter studies, it was concluded that this method is not representable. Therefore, it will not be discussed in the results and conclusion of this paper [10].

3.3. Setup

To execute the procedure, a simple setup must be determined. For this setup, the three groups that define a foundation will be used, namely the soil, the geometry, and the load.

3.3.1. Soil

In this study, two soil types are used, namely 'Sandy Clay' (CS) and 'Sand with traces of Fines' (S-F), in which clay is cohesive and sand cohesionless. The parameters that are used in the calculations are shown in Table 3-2.

Table 3-2: Ground parameters for Sandy Clay (CS) and Sand with traces of Fines (S-F), with the ranges of the influencing factors.

Parameters	**CS**	**S-F**	**Range**
Unit weight γ **(kN/m³)**	18.5	17.5	/
Saturated unit weight γ_{sat} **(kN/m³)**	20.5	19.5	17.5-30
Cohesion of soil c_u**(kPa)**	50	0	0-120
Effective internal friction angle φ' **(°)**	24.5	29.5	0-45
Adhesion α **(-)**	0.6	-	0-1.3
Bearing capacity coefficient β_p **(-)**	0.3	0.45	/
Angle of dispersion β **(-)**	10	15	/
Cone resistance q_c **(MPa)**	5	12.5	0.5-10 (clay) 10-25 (sand)

For the second calculation, a second soil is added for each type. With clay, a softer type will be added, while with sand more dense sand will be added. The parameters that change are shown in the following two tables.

Table 3-3: Fluctuating parameters for the transition to two layers, for Sandy Clay (CS)

	c_u **(kPa)**	β_p **(-)**	q_c **(MPa)**
Soft CS	**30**	**0.23**	**0.5**
Firm CS	**50**	**0.30**	**5**

Table 3-4: Fluctuating parameters for the transition to two layers, for Sand with traces of Fines (S-F)

	φ' (°)	q_c **(MPa)**
Medium dense S-F	29.5	12.5
Dense S-F	31.5	25

3.3.2. Geometry

For the geometry, a circular pile is chosen with a diameter of 0.6 meters and the length of the pile is 15 meters. For the parametric study, the diameter fluctuates between 0.20 meters and 2 meters and the pile length between 0.20 meters and 40 meters.

3.3.3. Load

Lastly, the load does not influence the bearing capacity of pile foundations. However, if a load is asked (in software programs), the inserted value has no influence.

3.4. Limitations

To narrow down this study, a few limitations, concerning the pile, the soil, the bearing capacity factors, and the bearing capacity were decided.

- The pile is a single pile made from concrete. It is a bored pile that is subjected to compression. The pile shape and base coefficients are equal to 1 and are not mentioned in the equations.
- The buckling potential of the piles is not considered.
- The soil is built up of one soil type, namely clay and sand. The soil is in a drained condition, thus all parameters will be 'effective'. Because of this built up no negative skin friction can be caused.
- The bearing capacity factors for the analytical calculation methods will be calculated using the equation of Meyerhof.
- The calculated bearing capacity is the design bearing capacity and not the calibrated bearing capacity. The calibrated bearing capacity for bored piles is calculated by applying a 1.15 safety factor.

4. Results and discussion

This section will discuss the results provided by the performed calculations, these are the parameter study and the transition from one to two layers. The curve progression tables displayed in the following paragraphs are derived from graphs. These graphs and the graphs shown in this chapter can be found in appendix B.

4.1. *Parameter study*

To discuss all the results, each parameter study is discussed separately. For each study, a table is given, showing how all the curves progress. Subsequently, the calculation formulas are given, and their differences are explained. For an interesting curve progression, a graph is disclosed.

4.1.1. SPT – Cohesive

In this parameter study, the CSN 73 1002 method only uses the Czech standard coefficients, thus making their results not representable. For the other methods, the following curve progressions can be concluded, shown in Table 4-1.

Table 4-1: Curve progressions of parameter studies for each parameter and calculation method.

	Smith's	**Ec7**	**NAVFAC DM 7.2**	**Effective Stress**
$c_{u,s}$	Linear	Linear	Linear	/
$c_{u,b}$	Linear	Linear	Linear	/
α	Linear	Linear	Linear	/
φ'	Tangent	Tangent	/	Linear
D	Hyp	Hyp	Hyp	Hyp
L	Linear	Linear	Linear	Hyp

*Hyp represents a hyperbolic progression of the curve

The following equations are used in the calculations, shown in Table 4-2. The total characteristic pile resistance is divided into the characteristic base resistance $R_{b,k}$ and the characteristic shaft resistance $R_{s,k}$.

Table 4-2: Cohesive soil equations for ground parameters.

	Smith's	**Ec7**	**NAVFAC DM 7.2**	**Effective Stress**
$R_{b,k}$	$N_c c_{u,b} A_b$	$N_c c_{u,b} A_b / \xi$	$9 c_{u,b} A_b$	$\sigma'_p N_p A_b$
$R_{s,k}$	$\alpha c_{u,s} O_s L$	$\alpha c_{u,s} O_s L / \xi$	$\alpha c_{u,s} O_s L$	$\beta_p \sigma'_v O_s L$

When comparing these equations, the first noticeable difference is the correlation factor ξ. The correlation factor ξ is only applied to Eurocode 7. The second difference relates to the bearing capacity factor N. It is calculated using Meyerhof, equation (5), for Eurocode 7 and Smith's, while NAVFAC DM 7.2 uses a constant value of nine, and in the effective stress method a different bearing capacity factor N_p is used, shown in Table 4-3.

Table 4-3: Range for N_p and β [11]

Type of soil	φ_{ef}	N_p	β
Clay	25 - 30	3 - 30	0.23 - 0.40
Silt	28 - 34	20 - 40	0.27 - 0.50
Sand	32 - 40	30 - 150	0.30 - 0.60
Gravel	35 - 45	60 - 300	0.35 - 0.80

*Values of Np must be interpolated

$$N_c = \left(\left(\tan^2\left(45 + \frac{\varphi'}{2}\right) * e^{\pi \tan \varphi'}\right) - 1\right) * \cot \varphi' \quad (5)$$

The last difference is related to the effective stress method, which does not use the undrained shear strength c_u, but the effective stress σ'. This method can be split up in two parts, effective stress without water (effective stress) and effective stress with water (effective stress w).

For the internal friction angle, shown in Figure 4.1, an interesting progression is noticed. Eurocode 7 and Smith's method show a tangential progression, while the effective stress method is constant. However, in the range of 25–30 degrees a linear increase can be seen. For Eurocode 7 and Smith's method, the bearing capacity factor is calculated using a tangent, while for the effective stress the bearing capacity factor is diverged from Table 4-3. This results in a linear increase within the range of 25–30 degrees.

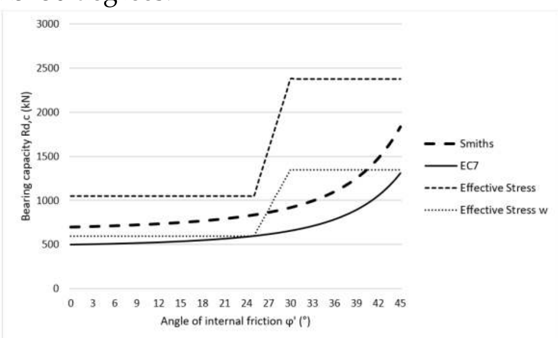


Figure 4.1: Parameter study of internal friction angle for SPT-Cohesive

In the calculation for the length, shown in Figure 4.2, the effective stress method has a different progression than the other methods. This is due to the fact that the effective stress method calculates the effective stress with the depth of the pile. The length of the pile is also used to calculate the shaft resistance, resulting in a squared effect and a hyperbolic curve. For the other methods, the length is only used once and is not squared, resulting in a linear progression.

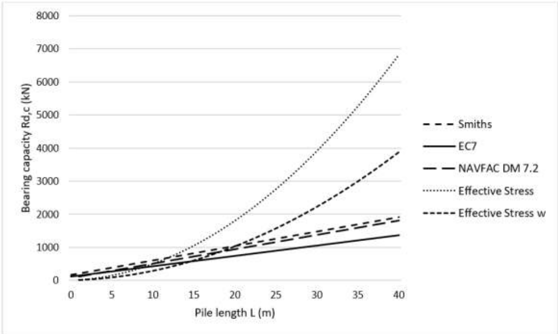


Figure 4.2: Parameter study of the pile length for SPT-Cohesive

4.1.2. CPT – Cohesive

In this parameter study, Smith's method has no calculation process in which CPT profiles are used. For the other methods, the following increases can be concluded, shown in Table 4-4.

Table 4-4: Curve progressions for each parameter and calculation method.

	Ec7	**Pile CPT**	**D-Foundations**
q_c	Linear*	Linear*	Linear*
D	Hyp	Hyp	Hyp
L	Linear	Linear	Linear*

*Linear with a small discrepancy; Hyp represents a hyperbolic progression of the curve

The following equations are used in the calculations, shown in Table 4-5. The total characteristic pile resistance is divided into the characteristic base resistance $R_{b,k}$ and the characteristic shaft resistance $R_{s,k}$.

Table 4-5: Cohesive soil equations for CPT profiles.

	Ec7	**Pile CPT**	**D-Foundations**
$R_{b,k}$	$A_b p_b / \xi$	$A_b p_b / \xi$	$A_b q_b \alpha_p / \xi$
$R_{s,k}$	$O_s L p_s / \xi$	$O_s L p_s / \xi$	$O_s L q_s \alpha_s / \xi$

In these calculations, the correlation factor is applied in each method. The equations for Eurocode 7 and *Pile CPT* are the same, while in *D-Foundations* the equation is slightly different.

For the characteristic base resistance, the unit base resistance p_b is calculated using (6):

$$p_b = 0.5\alpha_p \left(\frac{q_{c,I,mean}+q_{c,II,mean}}{2} + q_{c,III,mean}\right) \quad (6)$$

Where:

α_p = installation factor of the pile type

$q_{c,X,mean}$ = q_c, which is also q_b

For the characteristic shaft resistance, the unit shaft resistance p_s is calculated using (7)

$$p_s = q_{c,z}\alpha_s \quad (7)$$

Where:

$q_{c,z}$ = q_c ; α_s = installation factor of the shaft.

The installation factor of the shaft for *D-Foundations* is a different value than in Eurocode 7 and Smith's. For the friction resistance q_s is referred to Table 4-6.

Table 4-6: Calculation of friction resistance q_s [6]

Soil	q_c (MPa)	η^*_p (-) or q_s (MPa)	R_f^* (%)
Clay	1 – 4.5 > 4.5	η^*_p = 1/30 q_s = 0.150	3 – 6
Loam	1 – 6 > 6	η^*_p = 1/60 q_s = 0.100	2 – 3
Sandy clay/loam Sand/loam with clay	1 – 10 > 10	η^*_p = 1/80 q_s = 0.125	1 – 2
Sand	1 – 10 10 – 20 > 20	η^*_p = 1/90 q_s = 0.110 + 0.004 * (q_c -10) q_s = 0.150	< 1

An interesting progression can be seen in the cone penetration parameter study, shown in Figure 4.3.

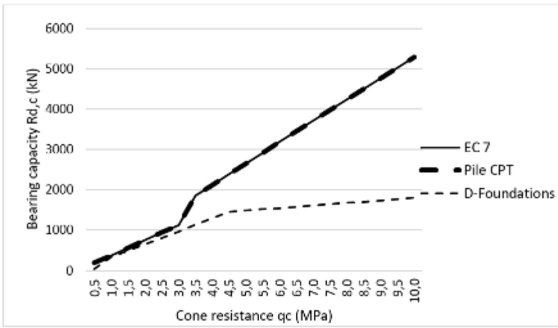


Figure 4.3: Parameter study cone resistance q_c for CPT-Cohesive

For the three curves, a linear progression can be noticed with a kink. In Eurocode 7 and *Pile CPT*, this kink finds its origin in the calculation process of the unit base resistance p_b. In *D-Foundations* the kink is due to the fact that at a cone resistance q_c of 4.5 and higher, the friction resistance q_s stays the same. This is because clay with a higher cone resistance do not occur. In *D-Foundations* the friction resistance at a cone resistance below 1 is equal to 0, resulting in a decrease in bearing capacity at 0.5 MPa.

The graph can be split into two zones: zone 1 where the bearing capacity is almost equal, and zone 2 in which the bearing capacity diverges.

$$Zone\ 1: q_c \leq 3$$
$$Zone\ 2: q_c > 3$$

For each zone, a parameter study is conducted on the length and the diameter. In zone 1 the bearing capacities slowly diverge with a small difference increasing with the parameter. In zone 2 a similar progression is found as in zone 1, but with a bigger dispersion. The parameter study of the diameter is shown as an example.

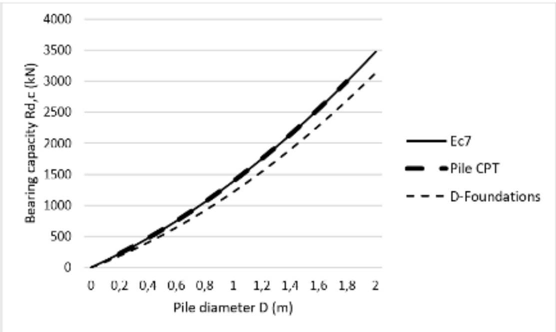


Figure 4.4: Parameter study of the pile diameter with a qc value of 2MPa for CPT-Cohesive

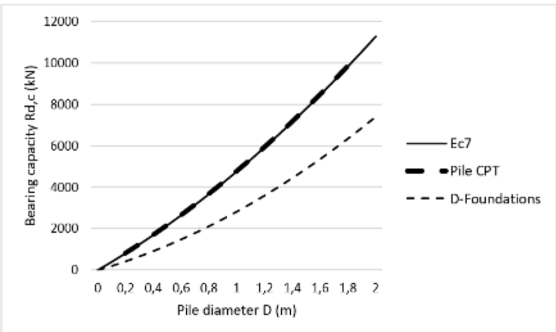


Figure 4.5: Parameter study of the pile diameter with a qc value of 5MPa for CPT-Cohesive

4.1.3. CPT - cohesionless

In this parameter study, Smith's method has no calculation for bored piles using CPT profiles. The following curve progressions are found for the remaining calculation methods:

Table 4-7: Curve progressions for each parameter and calculation method.

	Ec7	**Pile CPT**	**D-Foundations**
q_c	Linear*	Linear*	Linear*
D	Hyp	Hyp	Hyp
L	Linear	Linear	Linear*

*Linear with a small discrepancy

For this soil type, the same calculation formulas are used as shown in Table 4-5. Although, the parameters within the equations change. For Eurocode 7, the unit base resistance p_b and shaft resistance p_s are derived from a table [5], while these factors are still calculated using (6) and (7) for the *Pile CPT* program. In *D-Foundations* nothing changes, except for the friction resistance q_s, in which now sand is used instead of clay, shown in Table 4-6.

For the cone resistance q_c a range of 10-25 MPa is used. Table 4-6 shows us that for sand a calculation can be made below 10 MPa, but in the tables from Eurocode 7, no values are given below 10 MPa. This results in the following graph, Figure 4.6.

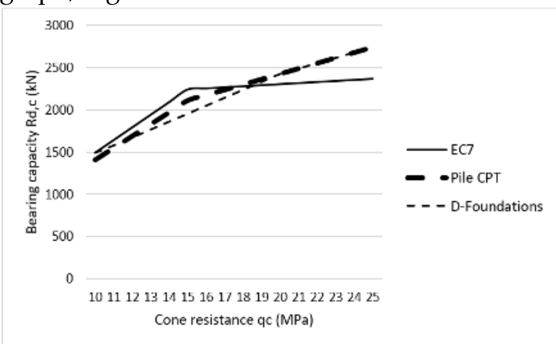


Figure 4.6: Parameter study cone resistance q_c for CPT-Cohesionless

Eurocode 7 has a linear increase until a cone resistance of 15 MPa, and after this, almost no upsurge is determined. Between *Pile CPT* and *D-Foundations*, a small difference can be noticed below 20 MPa, while at 20 MPa and higher the same bearing capacity is found.

4.2. Transition from one to two layers

To show the transition from one to two layers, Figure 4.7 is used as a reference. In the graph the ground transitions from a stiff sandy clay to a soft sandy clay, shown in Table 3-3.

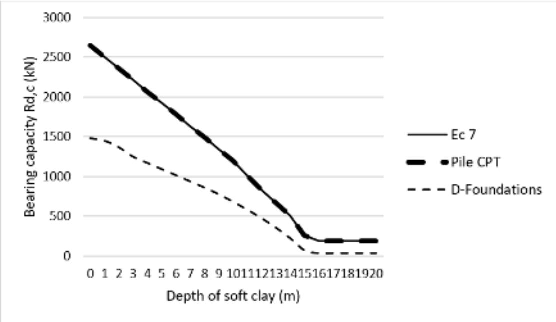


Figure 4.7: Transition from firm to soft clay for a CPT profile

When the soft sandy clay reaches higher depths than the pile length, the resulting bearing capacity for *D-Foundations* is almost 0. For Eurocode 7 and *Pile CPT*, the resulting bearing capacity is only a fraction of the original bearing capacity. During the transition, an almost linear decline is noticed for all three methods. The difference is due to the fact that *D-Foundations* applies a correction at a higher cone resistance, and below a cone resistance of 1 no friction resistance is taken into account.

For the other studies, a similar curve progression is concluded, but depending on the ground parameters, different bearing capacities are found.

5. Conclusions

In this section, a conclusion is described in which a final answer to the main research question 'What are the differences between Eurocode 7 and other calculation methods, for designing pile foundations?' is given. Table 5-1 shows a summary of which method to use in what situation.

Table 5-1: Summary of which calculation method to use

	Parameter	Calculation method
SPT - Cohesive	All	Eurocode 7
CPT - Cohesive	All	D-Foundations
CPT - Cohesionless	Length ≤ 13 m Length > 13 m	All D-Foundations
	Diameter ≤ 0.8 m Diameter > 0.8 m	All Eurocode 7
	qc ≤ 11 MPa 11MPa < qc < 19 MPa 19 MPa ≤ qc	Pile CPT D-Foundations Eurocode 7

5.1. SPT – Cohesive

For clay soils, the Eurocode can be seen as a safe method in every case, which may indicate that the Eurocode is conservative. When comparing it to the other analytical calculation method, Smith's, we can conclude that the Eurocode is safer, because Smith's does not apply a correlation factor.

For the *Pile CPT* program, the bearing capacity of NAVFAC DM 7.2 is located in between the results of Eurocode 7 and Smith's. This method is safe, however, not quite like the Eurocode. The effective stress method can be used when there is groundwater, otherwise very high bearing capacities are found in comparison to the other methods. When reaching a high pile length the effective stress method becomes unusable, namely for lengths bigger than 20 meters.

5.2. CPT – Cohesive

For clay soils, *Deltares* can be seen as the safest method. When acting within normal ranges of cone resistance, zone 1, all three methods are safe to use. When the cone resistance is located in zone 2, *Deltares* makes a good correction, while Eurocode 7 and *Pile CPT* do not.

5.3. CPT – Cohesionless

For sandy soils, *Deltares* and *Pile CPT* show many similarities, while Eurocode 7 diverges. This divergence results in a safer solution for higher diameters, while for higher lengths a less safe solution is presented by Eurocode 7. In the case of the cone resistance parameter, *Pile CPT* is the safest below 11 MPa, while between 11 and 19 MPa *D-Foundations* is safer. However, at higher values above 19 MPa, Eurocode 7 is the safest method. The diameter is the most influencing parameter, thus when the diameter is bigger than 0.8 meters, it is preferred to use Eurocode 7.

5.4. Transition into two layers

When a soil transitions from a homogeneous soil to a two-layered soil, the total bearing capacity slowly or rapidly increases/decreases with a linear progression.

The rate of decrease or increase depends on the influenced parameter and its magnitude. The curve increases when it transitions into a more bearing soil, while it decreases when it transitions into a less bearing soil.

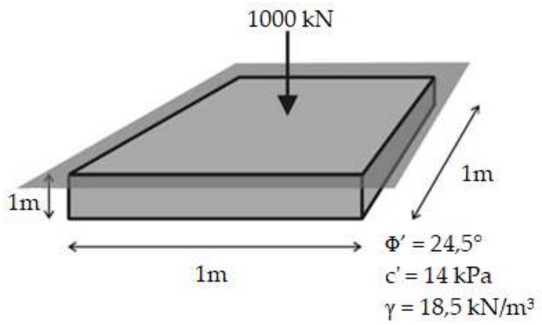
5.5. *Future research*

For future research many studies can still be done, a few are sorted below:

- on other types of piles, namely timber and steel.
- on different soil types, such as gravel, peat, and silt.
- on the influence of the bearing capacity factor, when working with different calculation methods.
- on a tensile or horizontal load.
- a ground setup where negative skin friction is possible.

Appendix A

In this addendum, a brief study about the comparison of three foundation types, namely strip foundations, plate foundations, and pile foundations, is disclosed. In this comparison, the same setup is used in the analytical calculation method of Eurocode 7 and both software programs: *Deltares* and *Geo5*.



	Eurocode 7 [kPa]	Deltares [kPa]	GEO5 [kPa]
Strip	419.03	307.66	419.03
Plate	419.03	402.21	419.03
Pile	463.04	/	570.00

When we compare the bearing capacity of strip foundations and plate foundations, we can deduce that both for the analytical calculation of Eurocode 7 and the numerical calculation of *Geo5*, the results are identical. The bearing capacity calculated for the two foundation types in *Deltares* differs considerably. This is due to the fact that in *Deltares*, an infinitely long strip foundation is used, which results in shape factors equal to 1 (the length appears in the denominator in the formula). As a result, the bearing capacity of the strip foundations is lower than the bearing capacity of the plate foundation.

For the comparison of pile foundations with the two other foundation types, the difference is found in the fact that pile foundations don't use ground safety coefficients, resulting in higher bearing capacity. When calculating the bearing capacity for pile foundations, a shaft and base resistance is taken into account, while the two other types of foundations only take into account the base resistance, resulting in a higher bearing capacity as well.

Appendix B

This appendix can be found digitally in the folder appendix B.

References

1. PALEN, G. *Paalfunderingen van de hoogste kwaliteit*. 2019; Available from: https://www.gvd-palen.be/paalfunderingen/.
2. Smith, I., *Smith's: Elements of soil mechanics*. 2006, West Sussex: John Wiley & Sons, Ltd. 490.
3. R.Janssens, *5-Geotechniek*. 2014, Universiteit Antwerpen. 313.
4. Stanley K. Suddarth, F.E.W., William L. Galligan, *Differential Reliability: Probabilistic engineering applied to wood members in bending/tension*. 1978: p. 16.
5. *Eurocode 7: Geotechnisch ontwerp*, in *NBN EN 1997*. 2004, CEN.
6. WTCB, *Richtlijnen voor de toepassing van Eurocode 7 in België*. 2008. **Deel1: Het grondmechanisch ontwerp in uiterste grenstoestand van axiaal op druk belaste funderingspalen**: p. 27.

7. *Deltares: Over ons*. [cited 2019; Available from: https://www.deltares.nl/nl/over-ons/.
8. *Geo5: Geotechnical software*. [cited 2019; Available from: https://www.finesoftware.eu/geotechnical-software/.
9. *Geo5: Analytical solution*. [cited 2019; Available from: https://www.finesoftware.eu/help/geo5/en/analytical-solution-01/.
10. A. Bond, A.H., *Decoding Eurocode 7*. 2008.
11. *Coefficients of pile bearing capacity*. [cited 2019; Available from: https://www.finesoftware.eu/help/geo5/en/coefficients-of-pile-bearing-capacity-01/.