Deltares

D-Pile Group 5.2 (Tilly 4.1 implementation)

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Limits and performances of the several models

1204328-000

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Title

D-Pile Group 5.2 (Tilly 4.1 implementation)

Project	Reference	Pages
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Version	Date	Author	Initials	Review	Initials	Approval	Initials
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State

draft

This is a draft report, intended for discussion purposes only. No part of this report may be relied upon by either principals or third parties.

Contents

1 Introduction

This report contains an overview of the calculations performed to test the limits and the performances of the different calculation models implemented in D-PILE GROUP:

- Two analytical models:
  - Poulos model
  - Plasti-Poulos model (using the Cap model for the calculation of the plasticity factors)
- Three more complex models differing on the pile-soil-pile interaction modelling but using the same finite element program TILLY:
  - Cap Interaction model
  - Cap Soil Interaction model (also known as Mindlin model)
  - Cap Layered Soil Interaction model
  - Dynamic model

The reference case used as basis for this analysis is a squared group of piles in a 2-layers system. The calculation time of the different models are compared and discussed. The influence of the following parameters is also analysed:

- Density of piles
- Type of pile
- Magnitude of the loads on the cap
- Type of loads on the cap
- Number of load-steps
- Top condition
- Oblique piles
- Pile length

Note that depending on the selected model, some of those parameters are not available.

Calculations were performed with D-PILE GROUP version 5.2.1.1 and TILLY 4.

The computer used has the following characteristics:

- Apple, Intel ic7 (2.93 GHz)
- 12 GB of RAM
- 64-bits system

2 Model Poulos

2.1 Poulos – ‘Reference case’

The case used as reference for Poulos model is based on Tutorial 8a of the user manual of D-PILE GROUP.

Cap loads

This reference case deals with the analysis of a pile group composed of a varying number of piles connected with a cap loaded by a vertical load of 320 kN and a lateral load of 80 kN.

Pile data

All piles consist of an open ended steel pipe with a length of 15 m, a diameter of 0.3 m, a wall thickness of 15 mm and a modulus of 2.1×10^8 kN/m^2. Their heads are fixed to the cap and their top level is at 0 m.

Pile positions
Piles have a rectangular distribution, with one meter centre-to-centre in both horizontal and vertical directions.

Soil interaction model
The elastic properties used for the interaction model are given in the table below.

Table 1: Pile-soil-pile interaction properties

	At surface level	**Below pile tip**
Young's modulus [kN/m^2]	3609	100000
Poisson ratio [-]	0.3	

2.2 Parametric study of influence

First, a reference calculation is performed using the 'Reference case' [§ 2.2.1]. Then, the influence of several parameters is investigated:
- [§ 2.2.2] Influence of the pile density
- [§ 2.2.3] Influence of the type of pile
- [§ 2.2.4] Influence of the cap loading
- [§ 2.2.5] Influence of the pile/cap connection

For each influencing parameter, at least three calculations are performed for three different number of piles (400, 900 and 1600 piles) and the calculation time is compared to the 'Reference case' for those three cases. If the average relative error is more than 5%, then the parameter is considered as influencing. If so, additional calculations will be performed for a larger number of piles. If not so, the parameter will be considered as not influencing.

2.2.1 Poulos – Results of the 'Reference case'

The number of piles varies from 25 to 2500, 2500 being the maximum number of piles allowed by D-PILE GROUP 5.2. Results of the calculation time as a function of the number of piles are given in Table 2 and also graphically represented in Figure 1, showing a power regression.

Table 2: Poulos model – Influence of the number of piles on the calculation time

Number of piles [-]	Calculation time [sec]	Number of equations [-]
25	0	131
100	0	506
225	1	1131
400	5	2006
625	19	3131
900	56	4506
1225	138	6131
1600	303	8006
2025	608	10131
2500	1131	12506

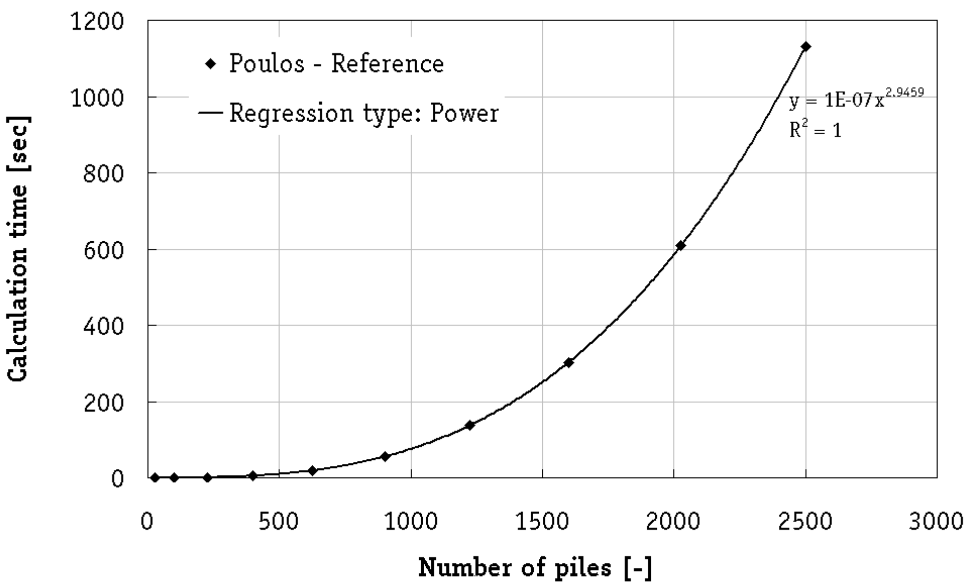

Figure 1 – Poulos model – Calculation time vs. number of piles for the Reference Case

2.2.2 Poulos – Influence of the pile density

The influence of the density of piles is investigated by decreasing the distance centre-to-centre to 0.5 m and increasing it to 2 m. This doesn't influence the calculation time as shown in Table 3.

Table 3: Poulos model – Influence of the pile density

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with ‘Reference case’ [%]	
Decrease density of piles	Distance between piles is 2 m instead of 1 m.	400	5	0.0	0.0
		900	56	0.0	
		1600	302	0.0	
Increase density of piles	Distance between piles is 0.5 m instead of 1 m.	400	5	0.0	-0.1
		900	56	0.0	
		1600	303	-0.3	

2.2.3 Poulos – Influence of the type of pile

Different changes on the pile are investigated: number of segments, material and length. Those changes don’t influence the calculation time as shown in the table below.

Table 4: Poulos model – Influence of the type of pile

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with ‘Reference case’ [%]	
User defined pile type	The pile includes 5 segments instead of 1.	400	5	0.0	0.7
		900	57	1.8	
		1600	304	0.3	
Square pile	Concrete square pile instead of round steel pile.	400	5	0.0	0.0
		900	56	0.0	
		1600	303	0.0	
Oblique pile	The rake (hor/vert) is 0.2 instead of 0.	400	5	0.0	0.8
		900	57	1.8	
		1600	305	0.7	
Pile length larger	Pile length is 30 m instead of 15 m.	400	5	0.0	0.0
		900	56	0.0	
		1600	303	0.0	
Pile length smaller	Pile length is 7.5 m instead of 15 m.	400	5	0.0	-0.1
		900	56	0.0	
		1600	302	-0.3	

2.2.4 Poulos – Influence of the cap loading

Different changes on the cap loading are investigated: magnitude of the forces, translations and number of load-steps. Those changes don’t influence the calculation time as shown in the table below.

Table 5: Poulos model – Influence of the cap loading

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Loads multiplied by 10	Loads on cap are multiplied by 10.	400	5	0.0	0.0
		900	56	0.0	
		1600	303	0.0	
Change loads into translations	Cap loaded by displacement of 0.08 m and -0.32 m resp. in X and Y direction.	400	5	0.0	0.0
		900	56	0.0	
		1600	303	0.0	
Decrease number of steps	The total number of load-steps is 2 instead of 20.	400	5	0.0	0.0
		900	56	0.0	
		1600	303	0.0	
Increase number of steps	The total number of load-steps is 200 instead of 20.	400	5	0.0	0.0
		900	56	0.0	
		1600	303	0.0	

2.2.5 Poulos – Influence of the pile/cap connection

The connection between each pile and the cap can either rotate freely ('free' head pile) or be completely fixed ('fixed' head pile). The type of connection considerably influences the calculation time as shown in the table below.

Table 6: Poulos model – Influence of the pile/cap connection

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Number of equations	Relative error with 'Reference case' [%]	
Pile/cap connection free	Pile/cap connection is Free instead of Fixed.	400	2	1206	-60.0	-65.9
		625	7	1881	-63.2	
		900	19	2706	-66.1	
		1225	46	3681	-66.7	
		1600	97	4806	-68.0	
		2025	191	6081	-68.6	
		2500	351	7506	-69.0	
Pile/cap connection mixed	Half of the pile/cap connections is Free and half is Fixed.	400	3	1606	-40.0	-41.5
		900	33	3606	-41.1	
		1296	95	5190	n.a.	
		1600	175	6406	-42.2	
		1936	305	7750	n.a.	
		2500	646	10006	-42.9	

As for the 'References case', both additional cases (i.e. 'free' or ''mixed' pile/cap connection) show a power regression as illustrated in the figure below.

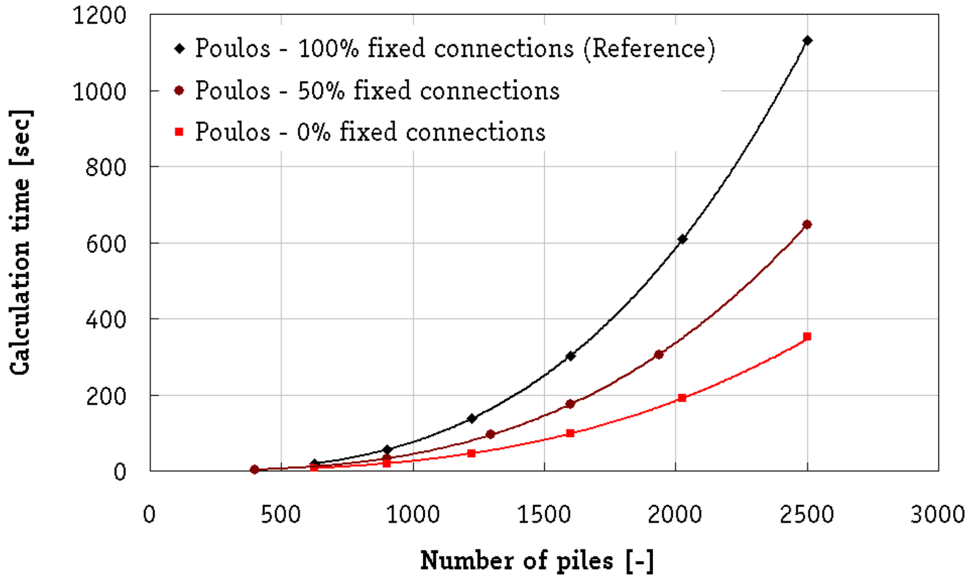

Figure 2 – Poulos model – Calculation time vs. number of piles for different percentages of fixed connections pile/cap

The Poulos model does not use the Tilly program, but consists of a separate module that generates and solves the applying equations according to Poulos' theory. The type of pile/cap connection influences the number of equations to be solved, and therefore the calculation time.

In order to estimate the influence of the number of load-steps on the calculation time, results of the three cases are shown in a logarithmic scale using the same slope as the Reference case. This leads to an average reduction of the calculation time of:

- $\frac{1.10\times10^{-7}-6.34\times10^{-8}}{1.10\times10^{-7}}=42.62\%$ for case with 50% of fixed connections
- $\frac{1.10\times10^{-7}-3.48\times10^{-8}}{1.10\times10^{-7}}=68.47\%$ for case with 0% of fixed connections

Those percentages are in accordance with the average relative error given in the table above..

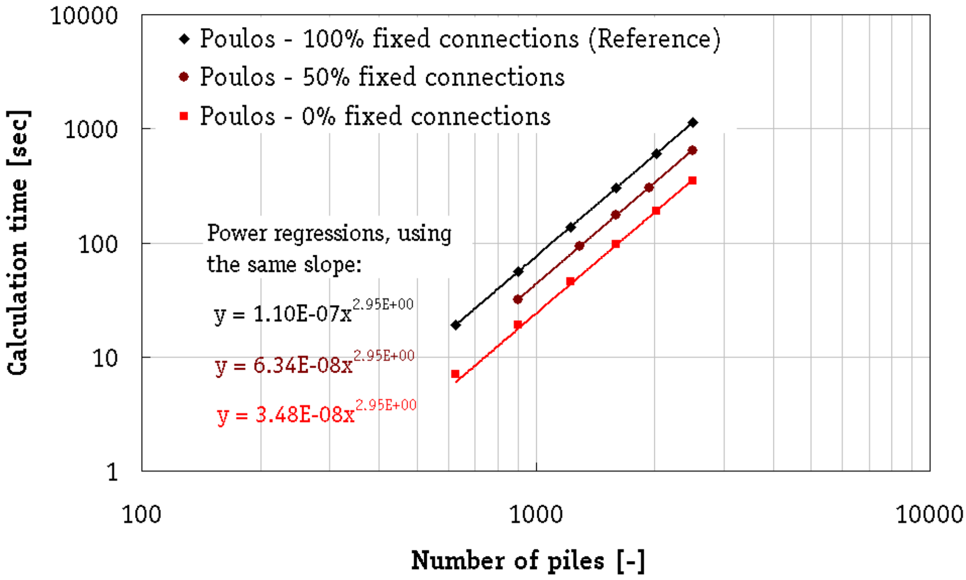

Figure 3 – Poulos model – Calculation time vs. number of piles for different percentages of fixed connections pile/cap

A polynomial relation of 2nd order between the reduction of the calculation time (compared to the 'Reference case') and the ratio between free and fixed connections can be extrapolated from Figure 4.

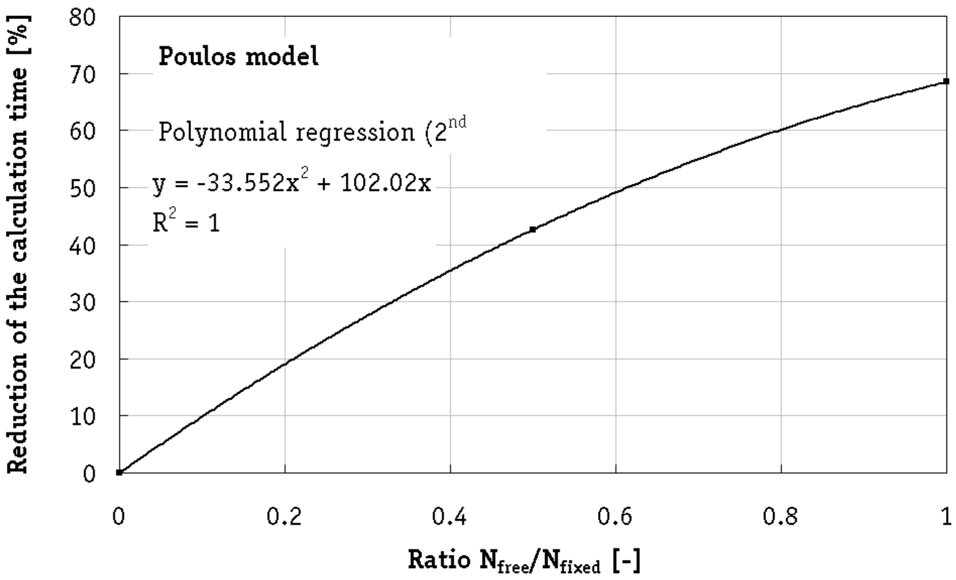

Figure 4 – Poulos model – Ratio between free and fixed connections vs. reduction of the calculation time

3 Model Plasti-Poulos

3.1 Plasti-Poulos – ‘Reference case’

The case used as reference for Plasti-Poulos model is the same as for Poulos model [§ 2.1] except for the soil data.

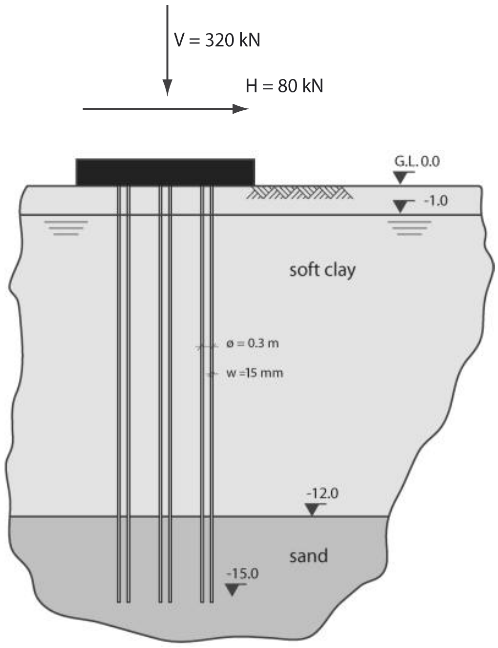

Figure 5 – Soil profile and pile group position for the ‘Reference case’

Soil data

The soil profile is composed of a soft clay and a sand layers.

Table 7: Soil properties for the ‘Reference case’

	Soft clay	**Sand**
Dry unit weight [kN/m³]	15	18
Wet unit weight [kN/m³]	15	20
Cu [kN/m²]	10	-
Friction angle [°]	-	35
Delta friction [°]	-	20
Cone resistance [kN/m²]	-	10000
Ko [-]	-	0.5
Lateral rule	API	API
Axial rule	API	API
J [-]	0.25	-
ε_{50} [-]	0.020	-
dz at 100 % [m]	0.0030	0.0025

Lateral and axial rules

The lateral P-Y and axial T-Z curves are taken according to the internationally accepted Code API for all layers.

3.2 Parametric study of influence

First, a reference calculation is performed using the ‘Reference case’ [§ 3.2.1]. Then, the influence of several parameters is investigated:

- [§ 3.2.2] Influence of the pile density
- [§ 3.2.3] Influence of the type of pile
- [§ 3.2.4] Influence of the cap loading
- [§ 3.2.5] Influence of the number of load-steps
- [§ 3.2.6] Influence of the required accuracy
- [§ 3.2.7] Influence of the relaxation factor
- [§ 3.2.8] Influence of the pile/cap connection

For each influencing parameter, at least three calculations are performed for three different number of piles (400, 625 and 900 piles) and the calculation time is compared to the ‘Reference case’ for those three cases. If the average relative error is more than 5%, then the parameter is considered as influencing. If so, additional calculations will be performed for a larger number of piles. If not so, the parameter will be considered as not influencing.

3.2.1 Plasti-Poulos – Results of the ‘Reference case’

The number of piles varies from 25 to 2500, 2500 being the maximum number of piles allowed by D-PILE GROUP 5.2. Results of the calculation time as a function of the number of piles are given in the table below and also graphically represented, showing a power regression.

Table 8: Plasti-Poulos model – Influence of the number of piles on the calculation time

Number of piles [-]	Calculation time [sec]		Ratio Plasti-Poulos / Poulos [-]
	Plasti-Poulos	Poulos	
25	0	0	0.00
100	4	0	-
225	23	1	23.00
400	111	5	22.20
625	392	19	20.63
900	1112	56	19.86
1225	2726	138	19.75
1600	5970	303	19.70
2025	11970	608	19.69
2500	22320	1131	19.73

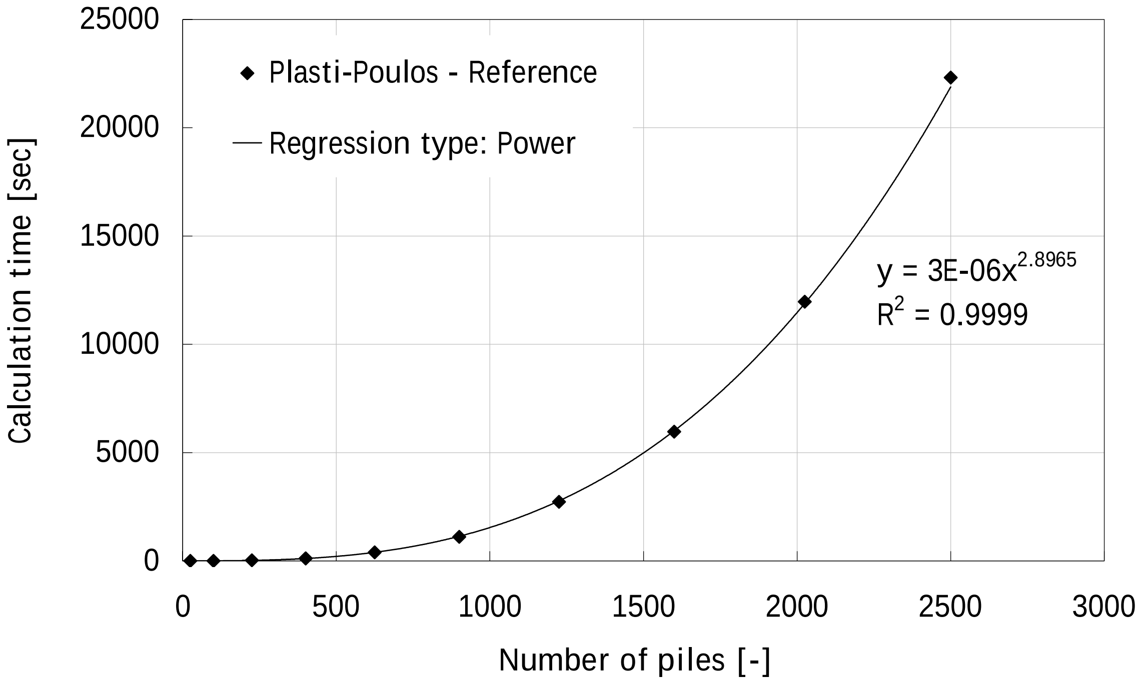

Figure 6 – Plasti-Poulos model – Calculation time vs. number of piles for the Reference Case

A comparison with the results found for Poulos model is presented in Figure 7, using a logarithmic scale and the same slope as the Plasti-Poulos model. As a conclusion, the calculation time with Plasti-Poulos model is 20 times longer than with Poulos model.

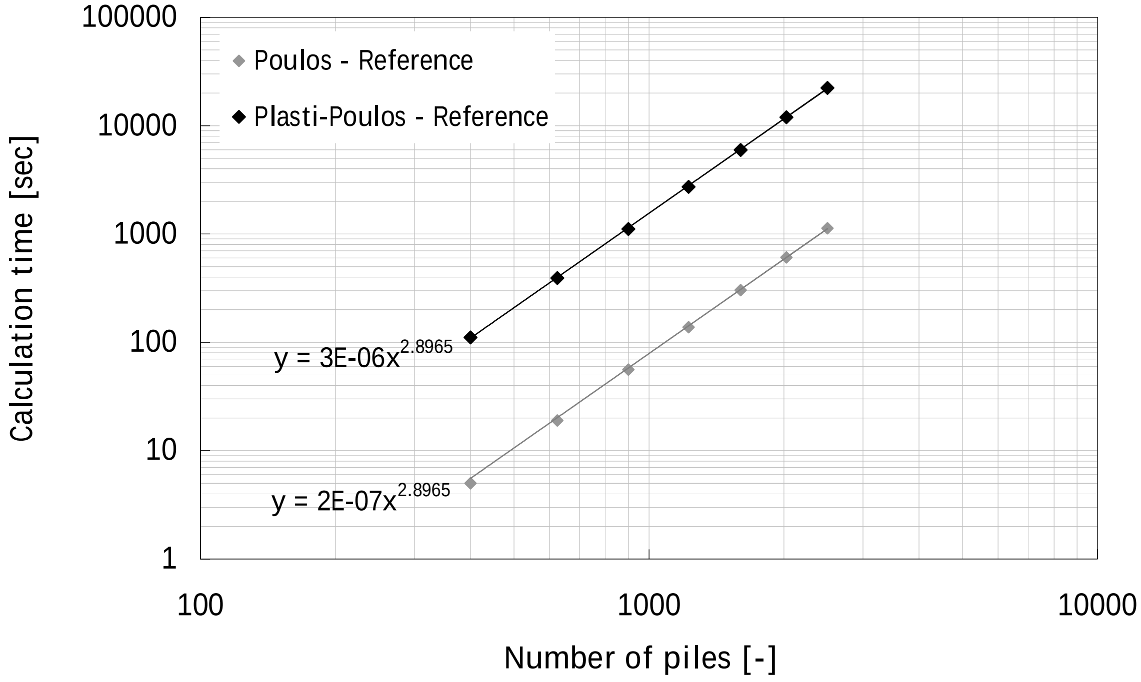

Figure 7 – Reference case – Comparison between Poulos and Plasti-Poulos models

3.2.2 Plasti-Poulos – Influence of the pile density

The influence of the density of piles is investigated by decreasing the distance centre-to-centre to 0.5 m and increasing it to 2 m. This doesn't influence the calculation time as shown in the table below.

Table 9: Plasti-Poulos model – Influence of the pile density

Influencing parameter	**Changing compare to Reference case**	**Number of piles**	**Calculation time [sec]**	**Relative error with 'Reference case' [%]**	
Decrease density of piles	Distance between piles is 2 m instead of 1 m.	400	110	-0.9	-0.5
		625	390	-0.5	
		900	1112	0.0	
Increase density of piles	Distance between piles is 0.5 m instead of 1 m.	400	110	-0.9	-0.5
		625	390	-0.5	
		900	1112	0.0	

3.2.3 Plasti-Poulos – Influence of the type of pile

Different changes on the pile are investigated: number of segments, material and length. Those changes don't influence the calculation time as shown in the table below.

Table 10: Poulos model – Influence of the type of pile

Influencing parameter	**Changing compare to Reference case**	**Number of piles**	**Calculation time [sec]**	**Relative error with 'Reference case' [%]**	
User defined pile type	The pile includes 5 segments instead of 1.	400	112	0.9	0.7
		625	394	0.5	
		900	1120	0.7	
Square pile	Concrete square pile instead of round steel pile.	400	112	0.9	1.0
		625	395	0.8	
		900	1126	1.3	
Oblique pile	The rake (hor/vert) is 0.2 instead of 0.	400	114	2.7	2.3
		625	400	2.0	
		900	1136	2.2	
Pile length larger	Pile length is 30 m instead of 15 m.	400	111	0.0	-0.2
		625	390	-0.5	
		900	1111	-0.1	
Pile length smaller	Pile length is 7.5 m instead of 15 m.	400	110	-0.9	-0.5
		625	390	-0.5	
		900	1111	-0.1	

3.2.4 Plasti-Poulos – Influence of the type of cap loading

Different changes on the cap loading are investigated: magnitude of the forces and type of load. Some changes influence the calculation time as shown in the table below.

Table 11: Plasti-Poulos model – Influence of the cap loading

Influencing parameter	**Changing compare to Reference case**	**Number of piles**	**Calculation time [sec]**	**Relative error with 'Reference case' [%]**	
Loads multiplied by 2	Loads on cap are multiplied by 2.	400	110	-0.9	-0.4
		625	389	-0.8	
		900	1117	0.4	
Change loads into translations	Cap loaded by displacement of 0.08 m and -0.32 m in X and Y direction respectively.	400	2201	1882.9	1823.1
		625	7010	1688.3	
		900	22219	1898.1	

The type of loads also influences the calculation time, as illustrated in the figure below. However, multiplying the magnitude of the forces by 2 does not influence the calculation time.

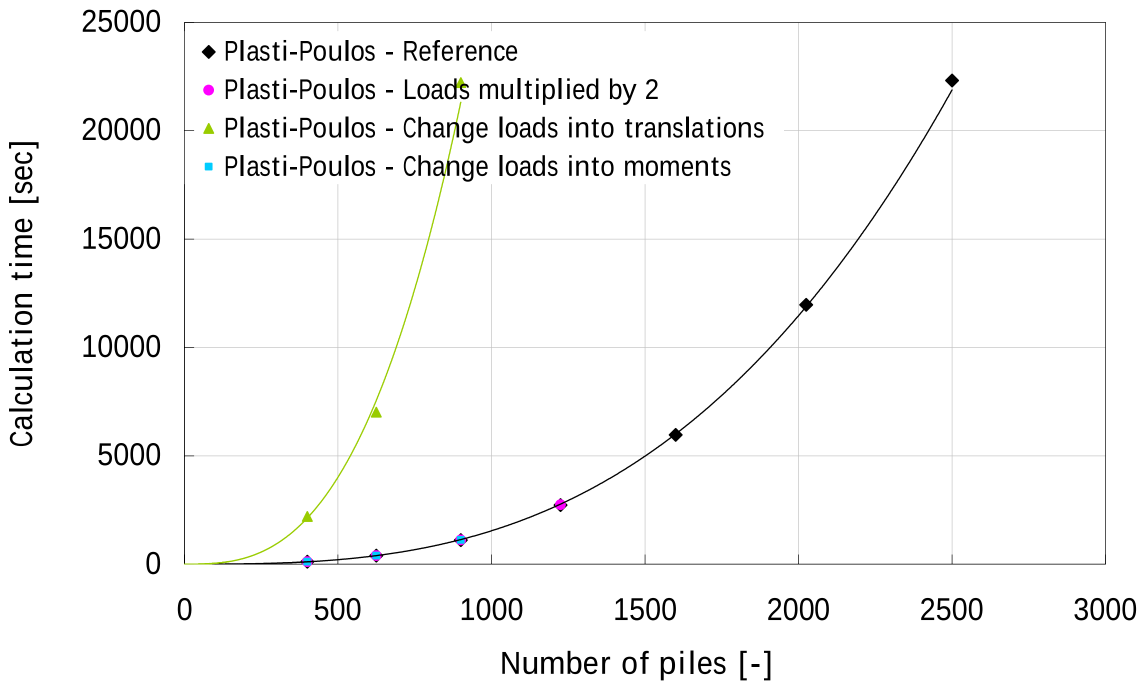

Figure 8 – Plasti-Poulos model – Calculation time vs. number of piles for different type of loads on the cap

A quantitative estimation of the type of loads is not possible as the number of load combinations and magnitude is too large. That's why no further analysis is carried out for the influence of the type of loads.

3.2.5 Plasti-Poulos – Influence of the number of load-steps

Increasing the number of load-steps will considerably increase the calculation time, as shown in the table below, because it will increase the number of calculations needed to show results for each steps. In the same way, decreasing the number of load-steps will considerably decrease the calculation time.

Table 12: Plasti-Poulos model – Influence of the number of load-steps

Influencing parameter	**Changing compare to Reference case**	**Number of piles**	**Calculation time [sec]**	**Relative error with 'Reference case' [%]**	
Decrease number of steps	The total number of load-steps is 2 instead of 20.	400	11	-90.1	-89.9
		625	39	-90.1	
		900	112	-89.9	
		1225	276	-89.9	
		1600	603	-89.9	
		2025	1209	-89.9	
		2500	2255	-89.9	
Increase number of steps	The total number of load-steps is 200 instead of 20.	400	1159	944.1	943.5
		625	4076	939.8	
		900	11638	946.6	

As for the 'Reference case', both additional cases (i.e. increase and decrease of the number of load-steps) show a power regression.

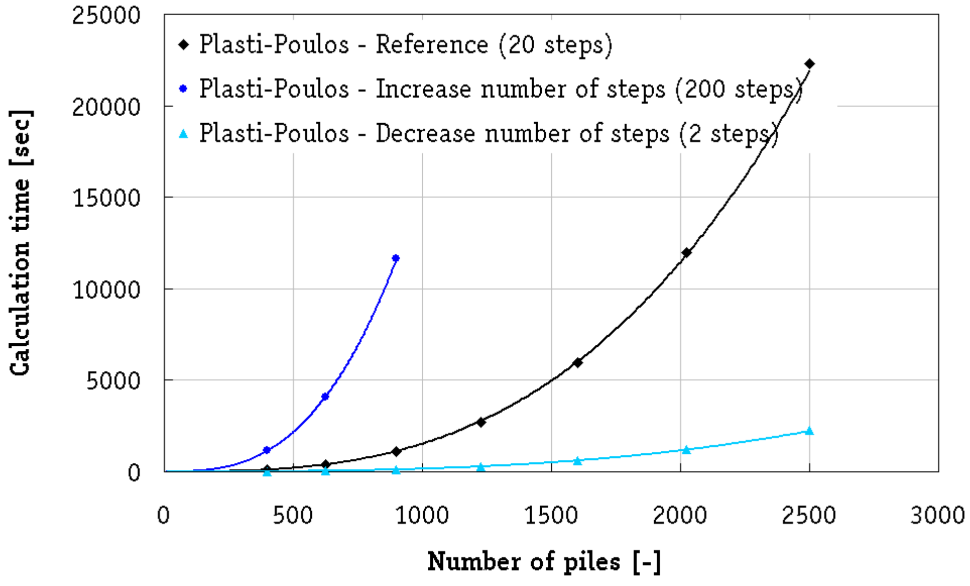

Figure 9 – Plasti-Poulos model – Calculation time vs. number of piles for different number of load-steps

In order to estimate the influence of the number of load-steps on the calculation time, results of the three cases (2, 20 and 200 load-steps) are shown in a logarithmic scale using the same slope as the Reference case. This leads to an average change of the calculation time of:

- $\frac{3.18\times10^{-6}-3.21\times10^{-7}}{3.18\times10^{-6}}=89.90\%$ for case with 2 load-steps
- $\frac{3.18\times10^{-6}-3.24\times10^{-5}}{3.18\times10^{-6}}=-920.55\%$ for case with 200 load-steps

Those percentages are in accordance with the average relative error given in the table above.

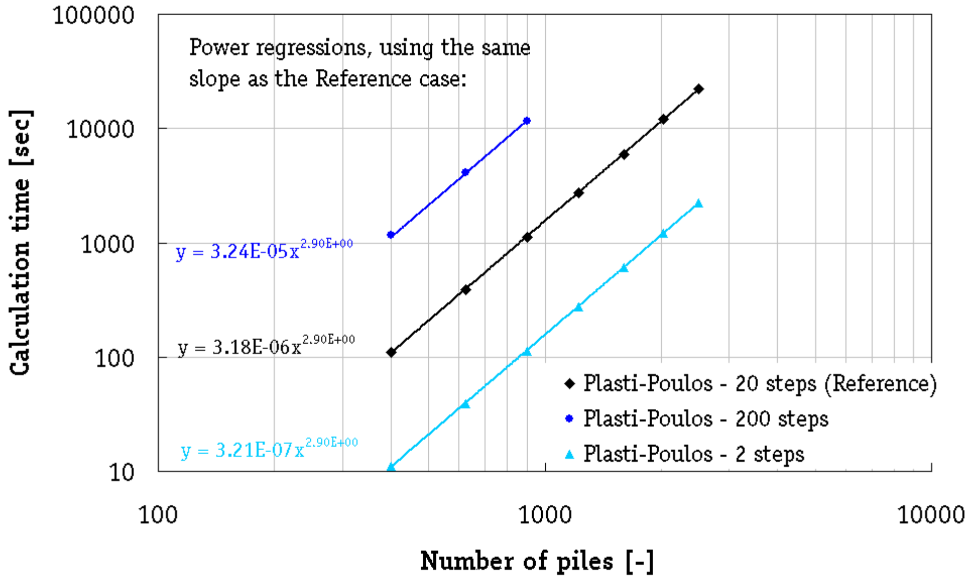

Figure 10 – Plasti-Poulos model – Calculation time vs. number of piles for different number of load-steps in a logarithmic scale

A linear relation between the change of the calculation time (compared to the 'Reference case') and the multiplication factor of the number of load-steps can be extrapolated from Figure 11.

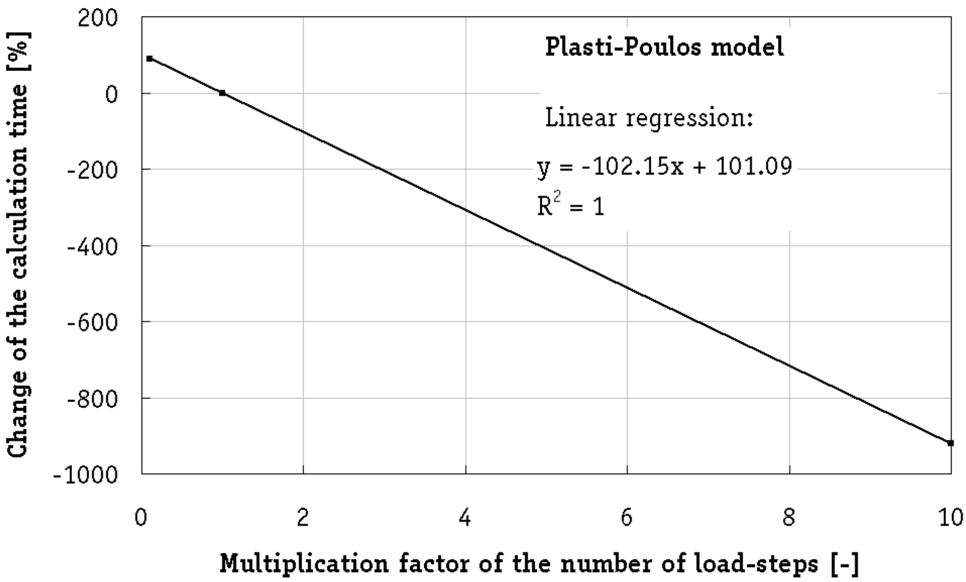

Figure 11 – Plasti-Poulos model – Change of the calculation time vs. multiplication factor of the number of load-steps

3.2.6 Plasti-Poulos – Influence of the required accuracy

The Plasti-Poulos model allows the user to enter a required accuracy for the main calculation. The Reference case uses a required accuracy of 10^{-3}. Decreasing it to 10^{-6} will considerably increase the calculation time, as shown in the table below, because it will increase the number of iteration needed to reached this required accuracy.

Table 13: Plasti-Poulos model – Influence of the required accuracy

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Increase required accuracy	The required accuracy is 0.1 instead of 10^{-3}.	400	110	-0.9	-0.5
		625	390	-0.5	
		900	1111	-0.1	
Decrease required accuracy	The required accuracy is 10^{-6} instead of 10^{-3}.	400	277	149.5	81.4
		625	833	112.5	
		900	1892	70.1	
		1225	3946	44.8	
		1600	7757	29.9	
Decrease required accuracy	The required accuracy is 10^{-9} instead of 10^{-3}.	400	736	563.1	338.9
		625	2010	412.8	
		900	4816	333.1	
		1225	9579	251.4	
		1600	13984	134.2	

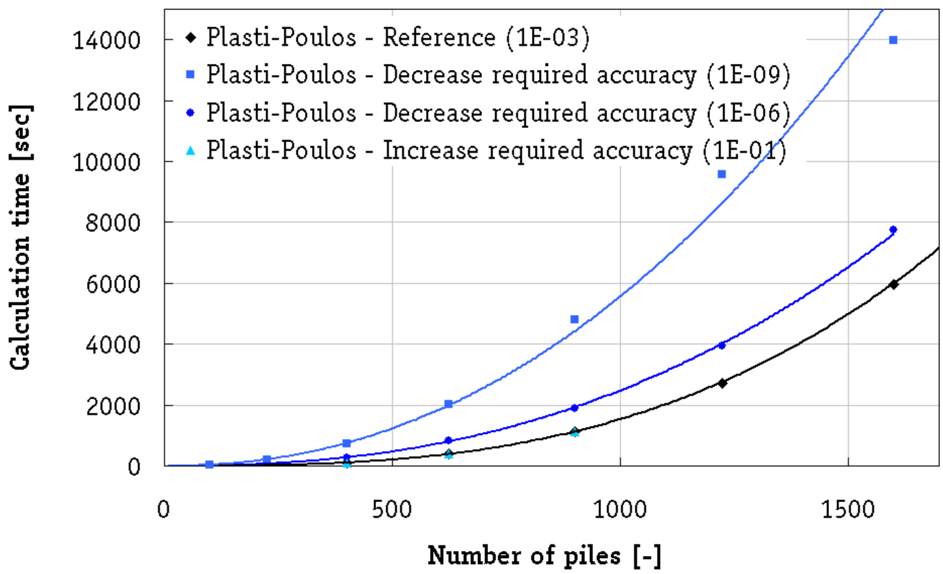

Figure 12 – Plasti-Poulos model – Calculation time vs. number of piles for different required accuracy

In order to estimate the influence of the required accuracy, results are shown in a logarithmic scale. The slope of the power regression of the three cases is not the same. Increasing the number of piles reduces the influence of the required accuracy.

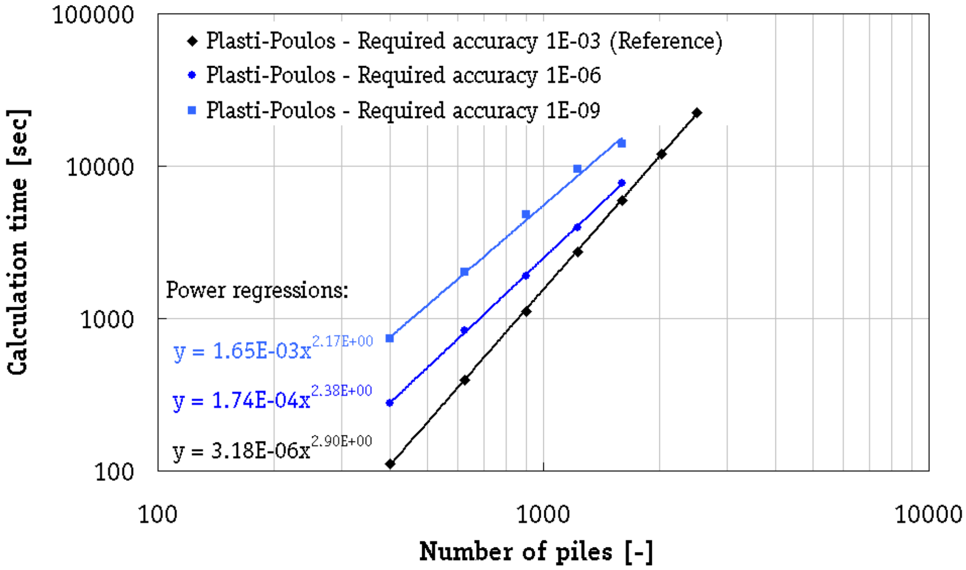

Figure 13 – Plasti-Poulos model – Calculation time vs. number of piles for different required accuracy in a logarithmic scale

A polynomial relation of 2nd order between the increase of the calculation time (compared to the 'Reference case') and the required accuracy can be extrapolated for different number of piles as shown in the figure below.

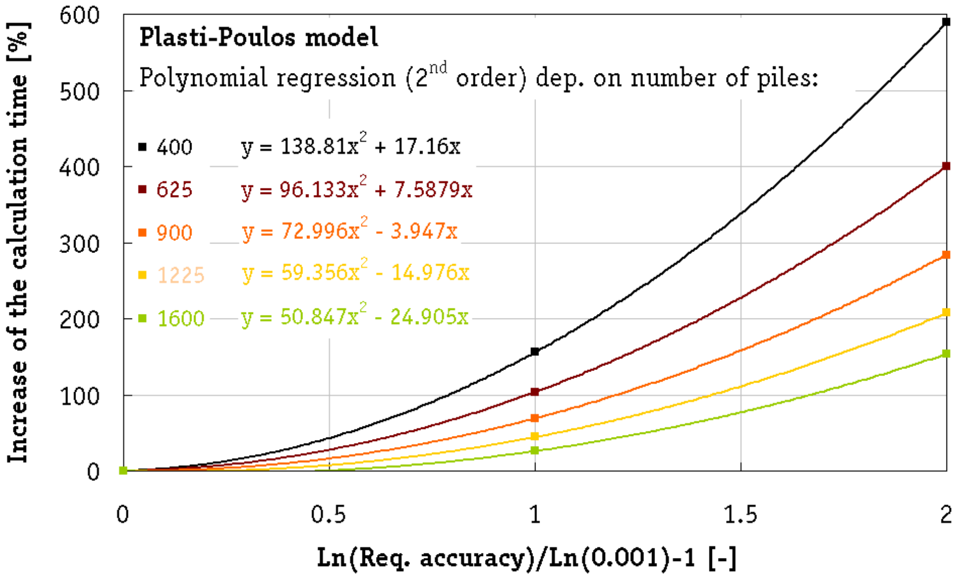

Figure 14 – Plasti-Poulos model – Increase of the calculation time vs. increase of the required accuracy

3.2.7 Plasti-Poulos – Influence of the relaxation factor

The Plasti-Poulos model allows the user to enter a relaxation factor for the main calculation. The Reference case uses a default relaxation factor of 0.6. Increasing it to 1 or decreasing it to 0.1 don't influence the calculation time as shown in the table below.

Table 14: Plasti-Poulos model – Influence of the relaxation factor

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Decrease relaxation factor	Relaxation factor is 0.1 instead of 0.6	400	111	0.0	0.1
		625	391	-0.3	
		900	1118	0.5	
Increase relaxation factor	Relaxation factor is 1 instead of 0.6	400	111	0.0	-0.2
		625	390	-0.5	
		900	1112	0.0	

3.2.8 Plasti-Poulos – Influence of the pile/cap connection

The connection between each pile and the cap can either rotate freely ('free' head pile) or be completely fixed ('fixed' head pile). The type of connection considerably influences the calculation time as shown in the table below.

Table 15: Plasti-Poulos model – Influence of the pile/cap connection

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Number of equations	Relative error with 'Reference case' [%]	
Pile/cap connection free	Pile/cap connection is Free instead of Fixed.	400	47	1206	-57.7	-64.6
		625	147	1881	-62.5	
		900	389	2706	-65.0	
		1225	914	3681	-66.5	
		1600	1934	4806	-67.6	
		2025	3801	6081	-68.2	
Pile/cap connection mixed	Half of the pile/cap connections is Free and half is Fixed.	400	71	1606	-36.0	-40.1
		900	667	3606	-40.0	
		1296	1891	5190	n.a.	
		1600	3476	6406	-41.8	
		1936	6078	7750	n.a.	
		2500	12852	10006	-42.4	
		2500	646	10006	-42.9	

As for the 'References case', both additional cases (i.e. 'free' or ''mixed' pile/cap connection) show a power regression as illustrated in the figure below.

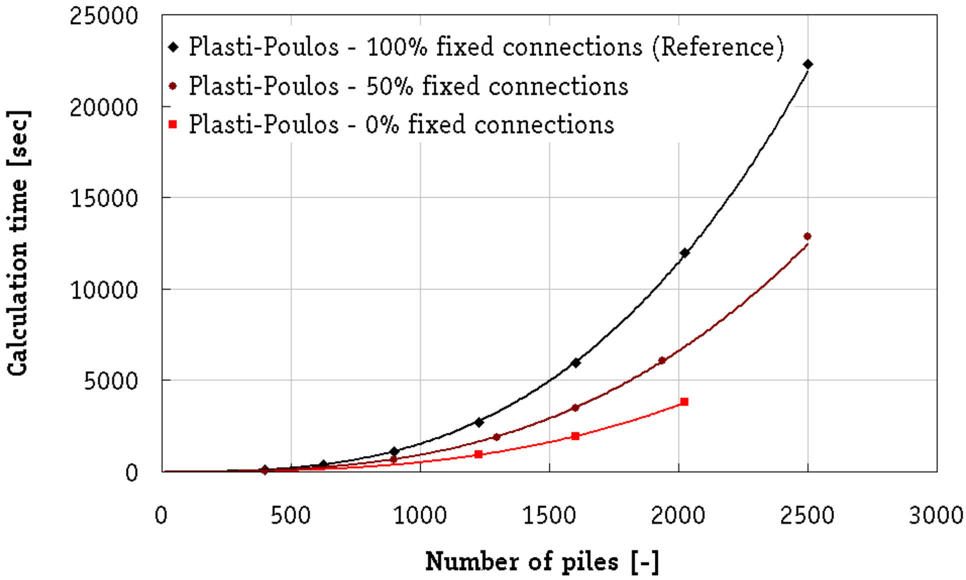

Figure 15 – Plasti-Poulos model – Calculation time vs. number of piles for different percentages of fixed connections pile/cap

The Plasti-Poulos model does not use the Tilly program for the main calculation, but consists of a separate module that generates and solves the applying equations according to Poulos' theory. The type of pile/cap connection influences the number of equations to be solved, and therefore the calculation time.

In order to estimate the influence of the number of load-steps on the calculation time, results of the three cases are shown in a logarithmic scale using the same slope as the Reference case. This leads to an average reduction of the calculation time of:

- $\frac{3.18\times10^{-6}-1.84\times10^{-6}}{3.18\times10^{-6}}=42.09\%$ for case with 50% of fixed connections
- $\frac{3.18\times10^{-6}-1.02\times10^{-6}}{3.18\times10^{-6}}=67.88\%$ for case with 0% of fixed connections

Those percentages are in accordance with the average relative error given in the table above and very close to the values found for Poulos model.

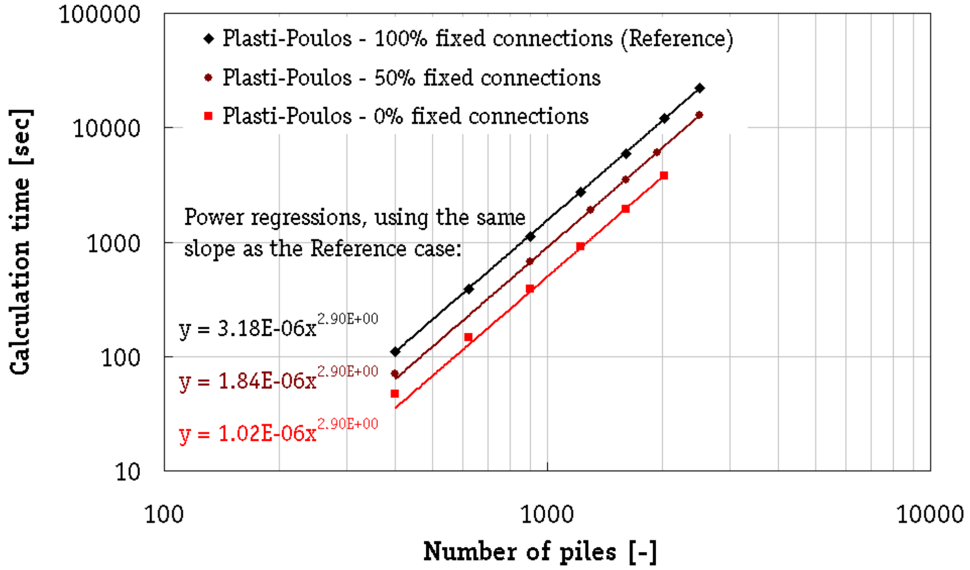

Figure 16 – Plasti-Poulos model – Calculation time vs. number of piles for different percentages of fixed connections pile/cap

A polynomial relation of 2nd order between the reduction of the calculation time (compared to the 'Reference case') and the ratio between free and fixed connections can be extrapolated from Figure 17.

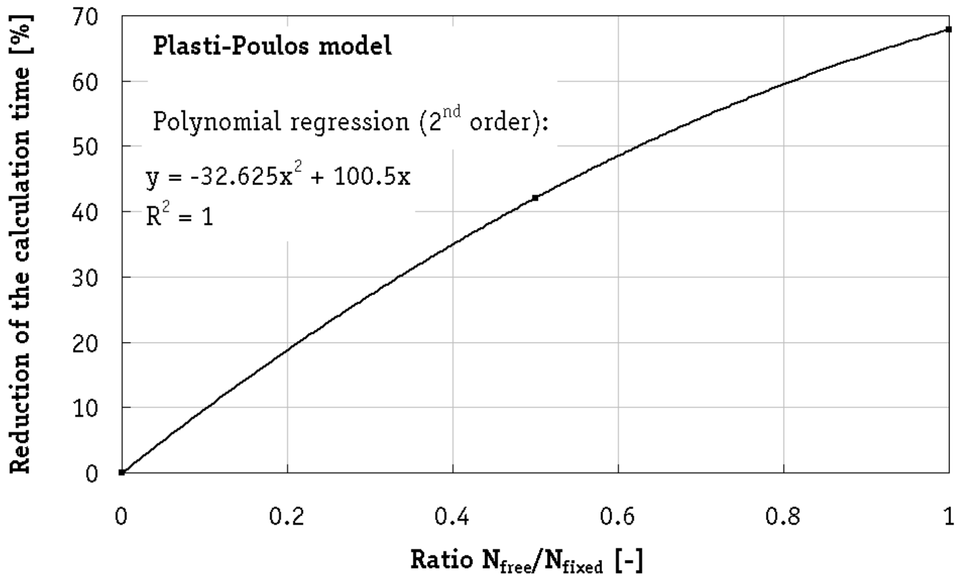

Figure 17 – Plasti-Poulos model – Ratio between free and fixed connections vs. reduction of the calculation time

4 Model Cap Interaction

4.1 Cap Interaction – 'Reference case'

The case used as reference for the Cap Interaction model uses the same input as Plasti-Poulos model [§ 3.1].

4.2 Parametric study of influence

First, a reference calculation is performed using the 'Reference case' [§ 4.2.1]. Then, the influence of several parameters is investigated:

- [§ 4.2.2] Influence of the pile density
- [§ 4.2.3] Influence of the type of pile
- [§ 4.2.4] Influence of the numbers of layers
- [§ 4.2.5] Influence of the cap loading
- [§ 4.2.6] Influence of the number of load-steps
- [§ 4.2.7] Influence of the required accuracy
- [§ 4.2.8] Influence of the pile/ cap connection
- [§ 4.2.9] Influence of the number of nodes along the pile

For each influencing parameter, at least three calculations are performed for three different number of piles (49, 100 and 144 piles) and the calculation time is compared to the 'Reference case' for those three cases. If the average relative error is more than 5%, then the parameter is considered as influencing. If so, additional calculations will be performed for a larger number of piles. If not so, the parameter will be considered as not influencing.

4.2.1 Cap Interaction – Results of the 'Reference case'

The number of piles varies from 9 to 676 (i.e. 26 × 26). More piles could be inputted in D-PILE GROUP however, the calculation time becomes too long (26 hours for 676 piles). Results of the calculation time as a function of the number of piles are given in the table below and also graphically represented, showing a power regression.

Table 16: Cap model – Influence of the number of piles on the calculation time

Number of piles [-]	Calculation time [sec]		Ratio Plasti-Poulos / Cap [-]
	Cap	Plasti-Poulos	
9	3		
25	16	0	-
49	70		
100	417	4	104.25
144	1121		
225	3828	23	166.43
256	5394		
289	7676		
324	10771		
400	19933	111	179.58
484	34754		
576	57770		
676	92189		

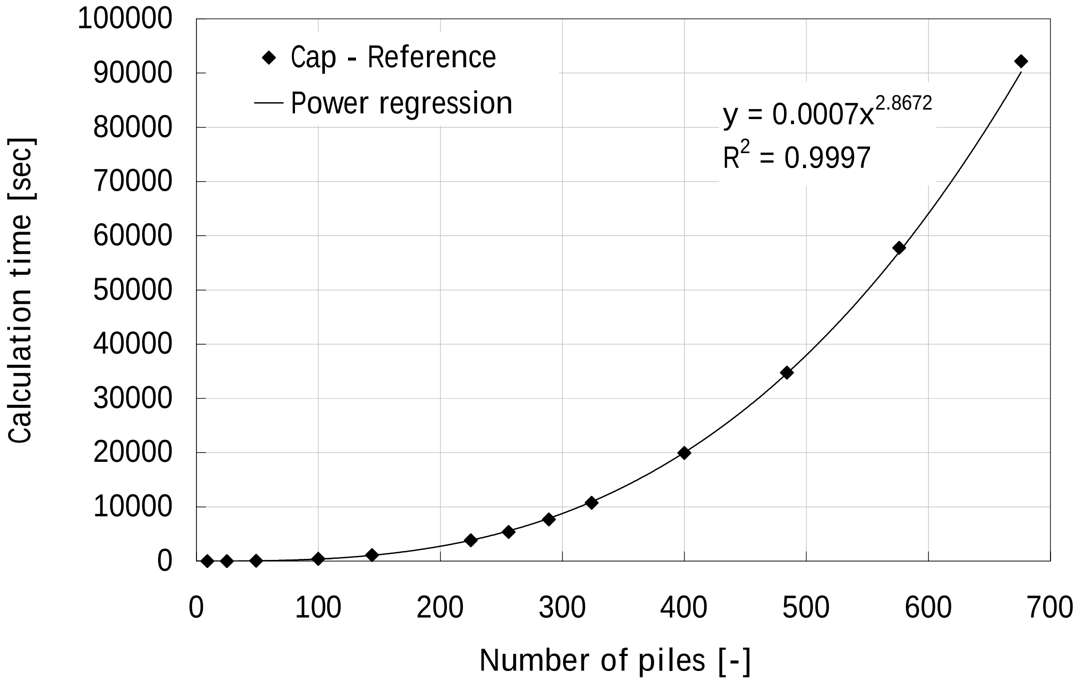

Figure 18 – Cap Interaction model – Calculation time vs. number of piles for the Reference case

A comparison with the results found for Plasti-Poulos model is presented in Figure *19*, using a logarithmic scale and the same slope as the Cap Interaction model. As a conclusion, the calculation time with Cap Interaction model is 176 times longer than with Plasti-Poulos model.

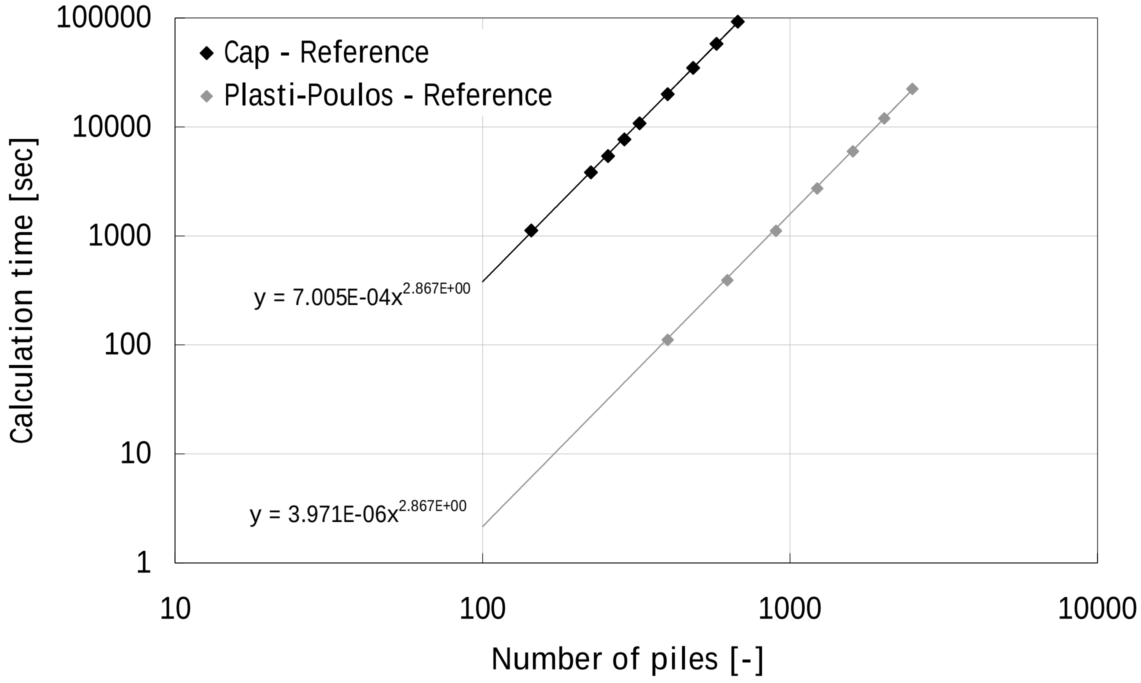

Figure 19 – Reference case – Comparison between Cap Interaction and Plasti-Poulos models

4.2.2 Cap Interaction – Influence of the pile density

The influence of the density of piles is investigated by decreasing the distance centre-to-centre to 0.5 m and increasing it to 2 m. This doesn't influence considerably the calculation time as shown in the table below.

Table 17: Cap Interaction model – Influence of the pile density

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Decrease density of piles	Distance between piles is 2 m instead of 1 m.	49	69	-1.4	-3.8
		100	395	-5.3	
		144	1070	-4.5	
Increase density of piles	Distance between piles is 0.5 m instead of 1 m.	49	70	0.0	2.1
		100	429	2.9	
		144	1158	3.3	

4.2.3 Cap Interaction – Influence of the type of pile

Different changes on the pile are investigated: number of segments, material and length. Those changes don't influence the calculation time as shown in the table below.

Table 18: Cap Interaction model – Influence of the type of pile

Influencing parameter	**Changing compare to Reference case**	**Number of piles**	**Calculation time [sec]**	**Relative error with 'Reference case' [%]**	
User defined pile type	The pile includes 5 segments instead of 1.	49	100	42.9	13.7
		100	442	6.0	
		144	1229	9.6	
		225	3690	-3.6	
Square pile	Concrete square pile instead of round steel pile.	49	70	0.0	-0.2
		100	416	-0.2	
		144	1116	-0.4	
Oblique pile	The rake (hor/vert) is 0.2 instead of 0.	49	69	-1.4	-2.9
		100	409	-1.9	
		144	1071	-4.5	
		225	3688	-3.7	

4.2.4 Cap Interaction – Influence of the number of layers

The number of layers is increased to 10, as shown in the table below, using all available types of material. This change influences the calculation time as shown in Figure 20. However, this influence seems to become negligible when the number of piles increases. That's why no further investigation is performed.

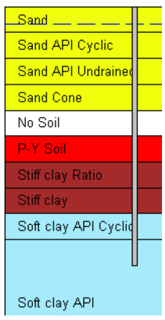

Figure 20 – Cap Interaction model – Distribution of the 10 soil layers to check the influence of the number of soil layers

Table 19: Cap Interaction model – Influence of the number of layers

Influencing parameter	**Changing compare to Reference case**	**Number of piles**	**Calculation time [sec]**	**Relative error with 'Reference case' [%]**	
Number of layers	The number of layers is increased to 10.	49	115	64.3	29.8
		100	493	18.2	
		144	1198	6.9	

4.2.5 Cap Interaction – Influence of the type of cap loading

Different changes on the cap loading are investigated: magnitude of the forces and type of load.

Table 20: Cap Interaction model – Influence of the cap loading

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with ‘Reference case’ [%]	
Loads multiplied by 10	Loads on cap are multiplied by 10.	49	73	4.3	4.3
		100	430	3.1	
		144	1181	5.4	
Change loads into translations	Cap loaded by displacement of 0.08 m and -0.32 m in X and Y direction respectively.	49	315	350.0	439.3
		100	2355	464.7	
		144	6762	503.2	
Soil displacements	Soil displacements is X and Z directions are added.	49	325	364.3	399.2
		100	2108	405.5	
		144	5916	427.7	

The type of loads influences the calculation time, as shown in the table. However, multiplying the magnitude of the forces by 10 does not influence the calculation time.

A quantitative estimation of the type of loads is not possible as the number of load combinations and magnitude is too large. That’s why no further analysis is carried out for the influence of the type of loads.

4.2.6 Cap Interaction – Influence of the number of load-steps

Increasing the number of load-steps will considerably increase the calculation time, as shown in the table below, because it will increase the number of calculations needed to show results for each steps. In the same way, decreasing the number of load-steps will considerably decrease the calculation time.

Table 21: Cap Interaction model – Influence of the number of load-steps

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with ‘Reference case’ [%]	
Increase number of steps	The total number of load-steps is 200 instead of 20.	49	552	688.6	749.4
		100	3633	771.2	
		144	9960	788.5	
Decrease number of steps	The total number of load-steps is 2 instead of 20.	49	20	-71.4	-81.0
		100	93	-77.7	
		144	181	-83.9	
		225	546	-85.7	
		289	1045	-86.4	

The same type of analysis as for the Plasti-Poulos model is performed [§ 3.2.5] and leads to an average change of the calculation time of:

- 85.89% for case with 2 load-steps
- -836.60 for case with 200 load-steps

Those percentages are in accordance with the average relative error given in the table.

A linear relation between the change of the calculation time (compared to the ‘Reference case’) and the multiplication factor of the number of load-steps can be extrapolated from Figure 21.

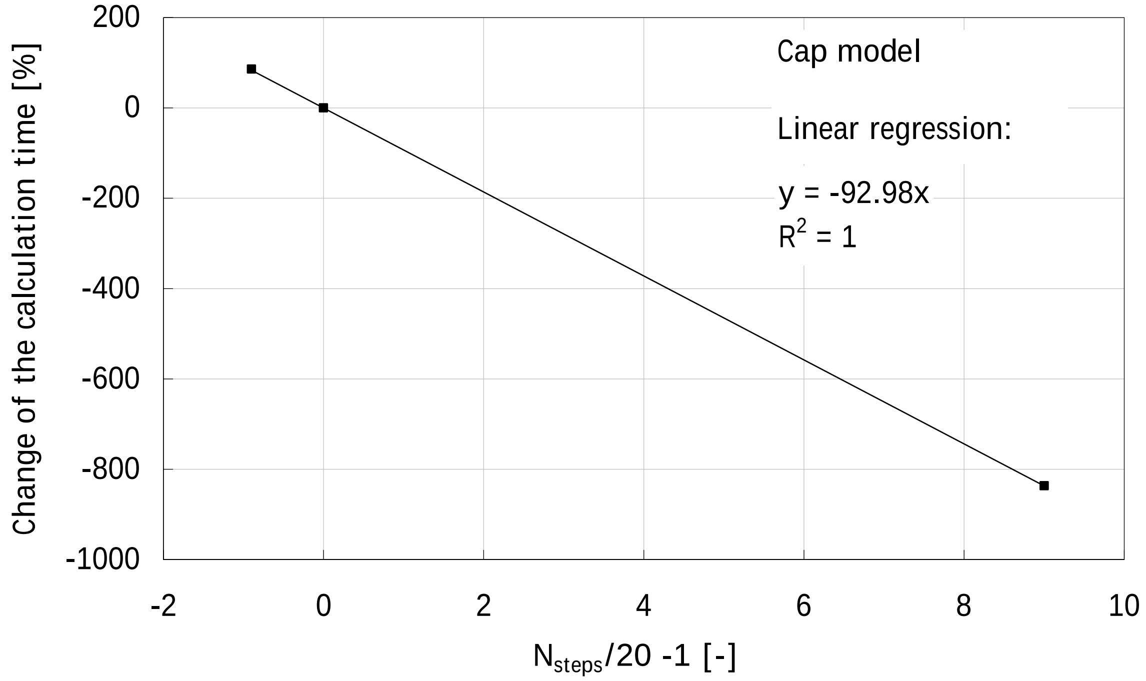

Figure 21 – Cap Interaction model – Change of the calculation time vs. multiplication factor of the number of load-steps

4.2.7 Cap Interaction – Influence of the required accuracy

The Cap model allows the user to change the default required accuracy. The Reference case uses a required accuracy of 10^{-3}. Decreasing it to 10^{-6} will considerably increase the calculation time, as shown in the table below, because it will increase the number of iteration needed to reached this required accuracy.

Table 22: Cap Interaction model – Influence of the required accuracy

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Increase required accuracy	The required accuracy is 0.1 instead of 10^{-3}.	49	70	0.0	-1.1
		100	422	1.2	
		144	1070	-4.5	
Decrease required accuracy	The required accuracy is 10^{-6} instead of 10^{-3}.	49	70	0.0	-1.3
		100	421	1.0	
		144	1068	-4.7	
Decrease required accuracy	The required accuracy is 10^{-9} instead of 10^{-3}.	49	67	-4.3	-3.1
		100	414	-0.7	
		144	1068	-4.7	
		225	3726	-2.7	

4.2.8 Cap Interaction – Influence of the pile/cap connection

The connection between each pile and the cap can either rotate freely ('free' head pile) or be completely fixed ('fixed' head pile). The type of connection doesn't influence too much the calculation time as shown in the table below.

Table 23: Cap Interaction model – Influence of the pile/cap connection

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Pile/cap connection free	Pile/cap connection is Free instead of Fixed.	49	66	-5.7	-4.5
		100	395	-5.3	
		144	1069	-4.6	
		225	3735	-2.4	

4.2.9 Cap Interaction – Influence of the number of nodes

Increasing the number of nodes along the pile will considerably increase the calculation time, as given in the table below, because it will increase the number of calculations needed to show results for each nodes. In the same way, decreasing the number of nodes will considerably decrease the calculation time.

Table 24: Cap Interaction model – Influence of the number of nodes

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Decrease number of nodes	The total number of nodes is 10 instead of 20.	49	34	-51.4	-51.5
		100	205	-50.8	
		144	529	-52.8	
		225	1883	-50.8	
Increase number of nodes	The total number of nodes is 40 instead of 20.	49	169	141.4	124.8
		100	953	128.5	
		144	2360	110.5	
		225	8373	118.7	

The same type of analysis as for the Plasti-Poulos model is performed [§ 3.2.5] and leads to an average change of the calculation time of:

- 51.06% for case with 10 nodes
- -118.52% for case with 40 load-steps

Those percentages are in accordance with the average relative error given in the table.

A linear relation between the change of the calculation time (compared to the 'Reference case') and the multiplication factor of the number of nodes can be extrapolated from Figure 22.

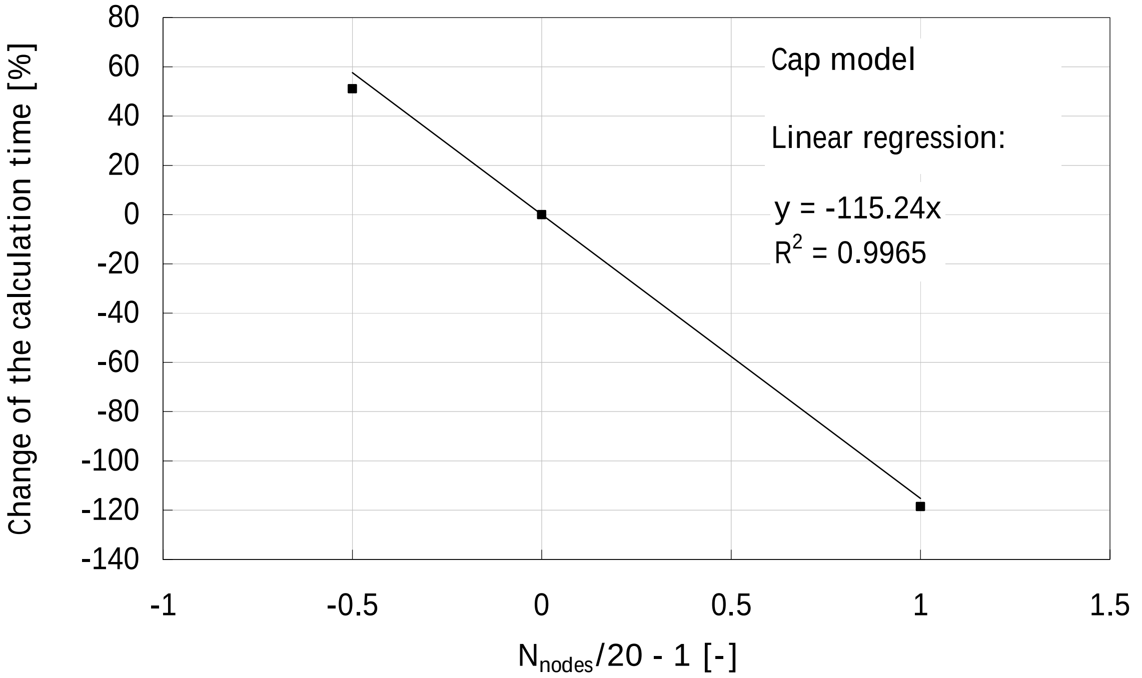

Figure 22 – Cap Interaction model – Change of the calculation time vs. multiplication factor of the number of nodes

5 Model Cap Soil Interaction (Mindlin)

5.1 Cap Soil Interaction – 'Reference case'

The case used as reference for the Cap Soil Interaction model is the same as for the Cap Interaction model [§ 4.1]. For the soil interaction behaviour, a Young's modulus of 5000 kN/m^2 and a Poisson ratio of 0.3 are used.

5.2 Parametric study of influence

First, a reference calculation is performed using the 'Reference case' [§ 5.2.1]. Then, the influence of several parameters is investigated:

- [§ 5.2.2] Influence of the pile density
- [§ 5.2.3] Influence of the type of pile
- [§ 5.2.4] Influence of the numbers of layers
- [§ 5.2.5] Influence of the cap loading
- [§ 5.2.6] Influence of the number of load-steps
- [§ 5.2.7] Influence of the required accuracy
- [§ 5.2.8] Influence of the pile/ cap connection
- [§ 5.2.9] Influence of the number of nodes along the pile

For each influencing parameter, at least three calculations are performed for three different number of piles (16, 25 and 36 piles) and the calculation time is compared to the 'Reference case' for those three cases. If the average relative error is more than 5%, then the parameter is considered as influencing. If so, additional calculations will be performed for a larger number of piles. If not so, the parameter will be considered as not influencing.

5.2.1 Cap Soil Interaction – Results of the 'Reference case'

The number of piles varies from 4 to 100 (i.e. 10 × 10). More piles could be inputted in D-PILE GROUP however, the calculation time becomes too long (8 hours for 100 piles). Results of the calculation time as a function of the number of piles are given in the table below and also graphically represented, showing a power regression.

Table 25: Cap Soil Interaction model – Influence of the number of piles on the calculation time

Number of piles [-]	Calculation time [sec]		Ratio Cap Soil / Cap [-]
	Cap Soil	Cap	
4	3		
9	26	3	8.67
16	121		
25	437		
36	1296		
49	3295	70	47.07
64	7427		
81	15002		
100	28260	417	67.77

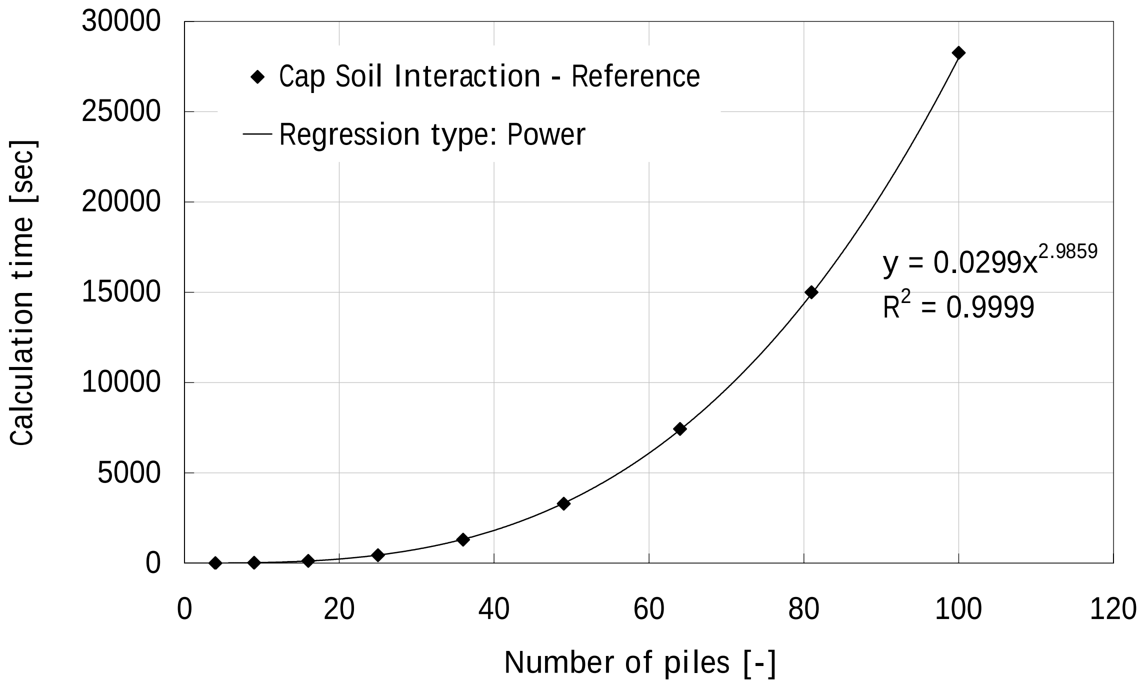

Figure 23 – Cap Soil Interaction model – Calculation time vs. number of piles for the Reference case

A comparison with the results found for Cap Interaction model is presented in Figure *24*, using a logarithmic scale and the same slope as the Cap Soil Interaction model. As a conclusion, the calculation time with Cap Soil Interaction model is 86 times longer than with Cap Interaction model.

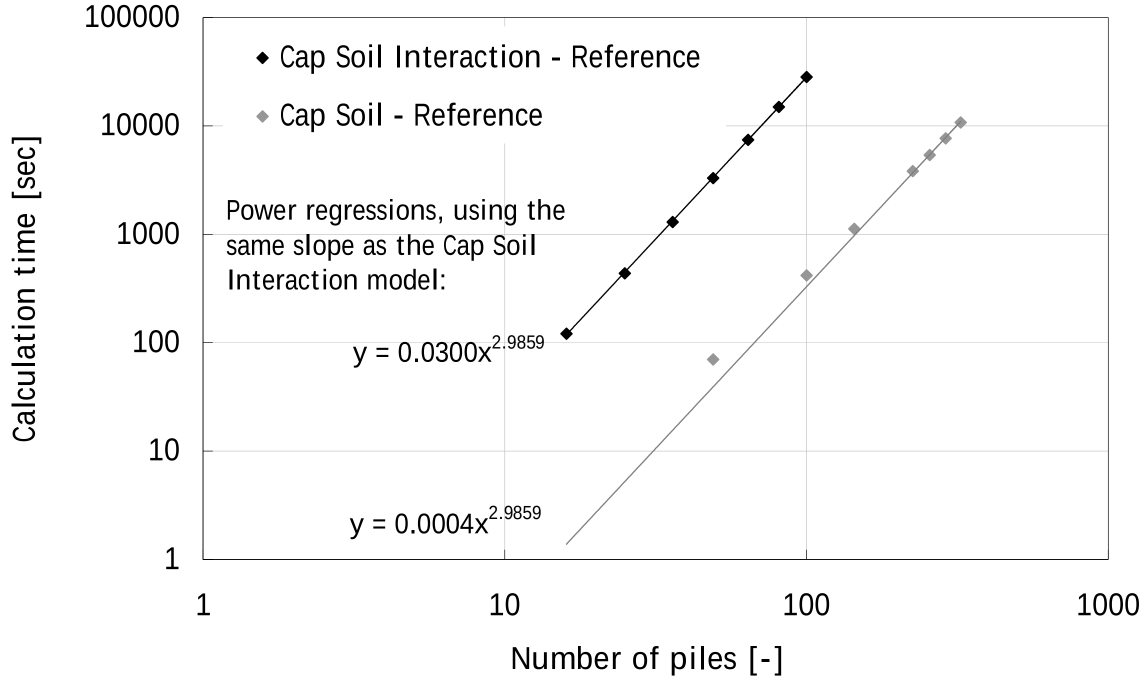

Figure 24 – Reference case – Comparison between Cap Soil Interaction and Cap Interaction models

5.2.2 Cap Soil Interaction – Influence of the pile density

The influence of the density of piles is investigated by decreasing the distance centre-to-centre to 0.5 m and increasing it to 2 m. This doesn't influence considerably the calculation time as shown in the table below.

Table 26: Cap Interaction model – Influence of the pile density

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Decrease density of piles	Distance between piles is 2 m instead of 1 m.	16	117	-3.3	-2.6
		25	429	-1.8	
Increase density of piles	Distance between piles is 0.5 m instead of 1 m.	16	119	-1.7	-0.8
		25	437	0.0	

5.2.3 Cap Soil Interaction – Influence of the type of pile

Different changes on the pile are investigated: number of segments, material and length. Those changes don't influence the calculation time as shown in the table below.

Table 27: Cap Interaction model – Influence of the type of pile

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
User defined pile type	The pile includes 5 segments instead of 1.	16	138	14.0	5.7
		25	462	5.7	
		36	1262	-2.6	
Square pile	Concrete square pile instead of round steel pile.	16	119	-1.7	-1.7
		25	429	-1.8	
Oblique pile	The rake (hor/vert) is 0.2 instead of 0.	16	115	-5.0	3.9
		25	522	19.5	
		36	1259	-2.9	

5.2.4 Cap Soil Interaction – Influence of the number of layers

The number of layers is increased to 10, as for the Cap Interaction model. This change influences the calculation time as shown in the table below. However, this influence seems to become negligible when the number of piles increases. That's why no further investigation is performed.

Table 28: Cap Soil Interaction model – Influence of the number of layers

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Number of layers	The number of layers is increased to 10.	16	127	5.0	2.6
		25	456	4.3	
		36	1311	1.2	
		49	3296	0.0	

5.2.5 Cap Soil Interaction – Influence of the type of cap loading

Different changes on the cap loading are investigated: magnitude of the forces and type of load.

Table 29: Cap Soil Interaction model – Influence of the cap loading

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Loads multiplied by 10	Loads on cap are multiplied by 10.	16	236	95.0	72.9
		25	843	92.9	
		36	2250	73.6	
		49	4601	39.6	
		64	12143	63.5	
Change loads into translations	Cap loaded by displacement of 0.08 m and -0.32 m in X and Y direction respectively.	16	734	506.6	242.0
		25	1205	175.7	
		36	3739	188.5	
		49	9112	176.5	
		64	19503	162.6	

The type of load and the magnitude of the forces influence the calculation time, as shown in the table above.

A quantitative estimation of the type of loads is not possible as the number of load combinations and magnitude is too large. That's why no further analysis is carried out for the influence of the type of loads.

5.2.6 Cap Soil Interaction – Influence of the number of load-steps

Increasing the number of load-steps will considerably increase the calculation time, as shown in the table below, because it will increase the number of calculations needed to show results for each steps. In the same way, decreasing the number of load-steps will considerably decrease the calculation time.

Table 30: Cap Soil Interaction model – Influence of the number of load-steps

Influencing parameter	**Changing compare to Reference case**	**Number of piles**	**Calculation time [sec]**	**Relative error with 'Reference case' [%]**	
Increase number of steps	The total number of load-steps is 200 instead of 20.	16	955	689.3	711.0
		25	3590	721.5	
		36	10635	720.6	
		49	26770	712.4	
Decrease number of steps	The total number of load-steps is 2 instead of 20.	16	29	-76.0	-78.4
		25	97	-77.8	
		36	267	-79.4	
		49	716	-78.3	
		64	1441	-80.6	

The same type of analysis as for the Plasti-Poulos model is performed [§ 3.2.5] and leads to an average change of the calculation time of:

- 79.92% for case with 2 load-steps
- -699.52% for case with 200 load-steps

Those percentages are in accordance with the average relative error given in the table.

A linear relation between the change of the calculation time (compared to the 'Reference case') and the multiplication factor of the number of load-steps can be extrapolated.

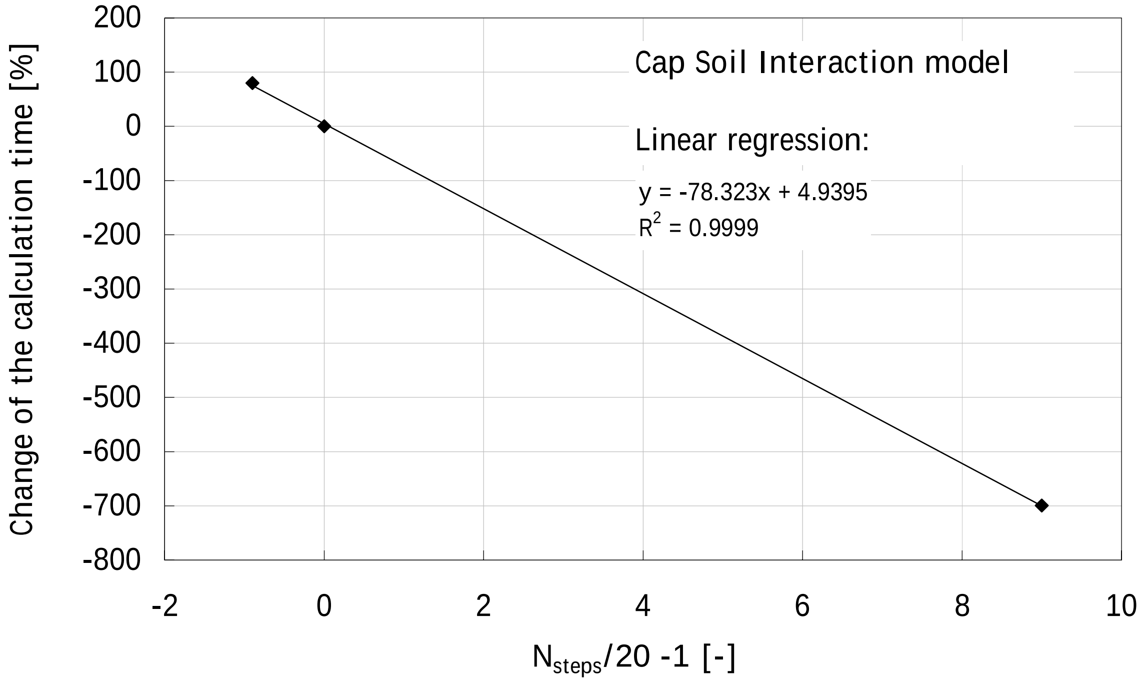

Figure 25 – Cap Soil Interaction model – Change of the calculation time vs. multiplication factor of the number of load-steps

5.2.7 Cap Soil Interaction – Influence of the required accuracy

The Reference case uses a required accuracy of 10^{-3}. Decreasing or increasing it doesn't influence the calculation time, as shown in the table below.

Table 31: Cap Soil Interaction model – Influence of the required accuracy

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Increase required accuracy	The required accuracy is 10^{-9} instead of 10^{-3}.	16	119	-1.7	-1.8
		25	428	-2.1	
		36	1276	-1.5	
Decrease required accuracy	The required accuracy is 10^{-6} instead of 10^{-3}.	16	119	-1.7	-1.8
		25	428	-2.1	
		36	1274	-1.7	
Increase required accuracy	The required accuracy is 10^{-1} instead of 10^{-3}.	16	118	-2.5	-2.0
		25	429	-1.8	
		36	1274	-1.7	
		225	3726	-2.7	

5.2.8 Cap Soil Interaction – Influence of the pile/cap connection

The connection between each pile and the cap can either rotate freely ('free' head pile) or be completely fixed ('fixed' head pile). The type of connection doesn't influence too much the calculation time as shown in the table below.

Table 32: Cap Soil Interaction model – Influence of the pile/cap connection

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Pile/cap connection free	Pile/cap connection is Free instead of Fixed.	16	121	0.0	-6.7
		25	437	0.0	
		36	1223	-5.6	
		49	2984	-9.4	
		64	6621	-10.9	
		81	12886	-14.1	

5.2.9 Cap Soil Interaction – Influence of the number of nodes

Increasing the number of nodes along the pile will considerably increase the calculation time, as illustrated in the table below, because it will increase the number of calculations needed to show results for each nodes. In the same way, decreasing the number of nodes will considerably decrease the calculation time.

Table 33: Cap Interaction model – Influence of the number of nodes

Influencing parameter	Changing compare to Reference case	Number of piles	Calculation time [sec]	Relative error with 'Reference case' [%]	
Decrease number of nodes	The total number of nodes is 10 instead of 20.	16	23	-81.0	-81.7
		25	80	-81.7	
		36	240	-81.5	
		49	578	-82.5	
		64	1328	-82.1	
		81	2671	-82.2	
		100	4956	-82.5	
Increase number of nodes	The total number of nodes is 40 instead of 20.	16	748	518.2	527.2
		25	2678	512.8	
		36	8430	550.5	
		225	8373	118.7	

The same type of analysis as for the Plasti-Poulos model is performed [§ 3.2.5] and leads to an average change of the calculation time of:

- 82.32% for case with 10 nodes
- -523.56% for case with 40 load-steps

Those percentages are in accordance with the average relative error given in the table.

A polynomial relation between the change of the calculation time (compared to the 'Reference case') and the multiplication factor of the number of nodes can be extrapolated.

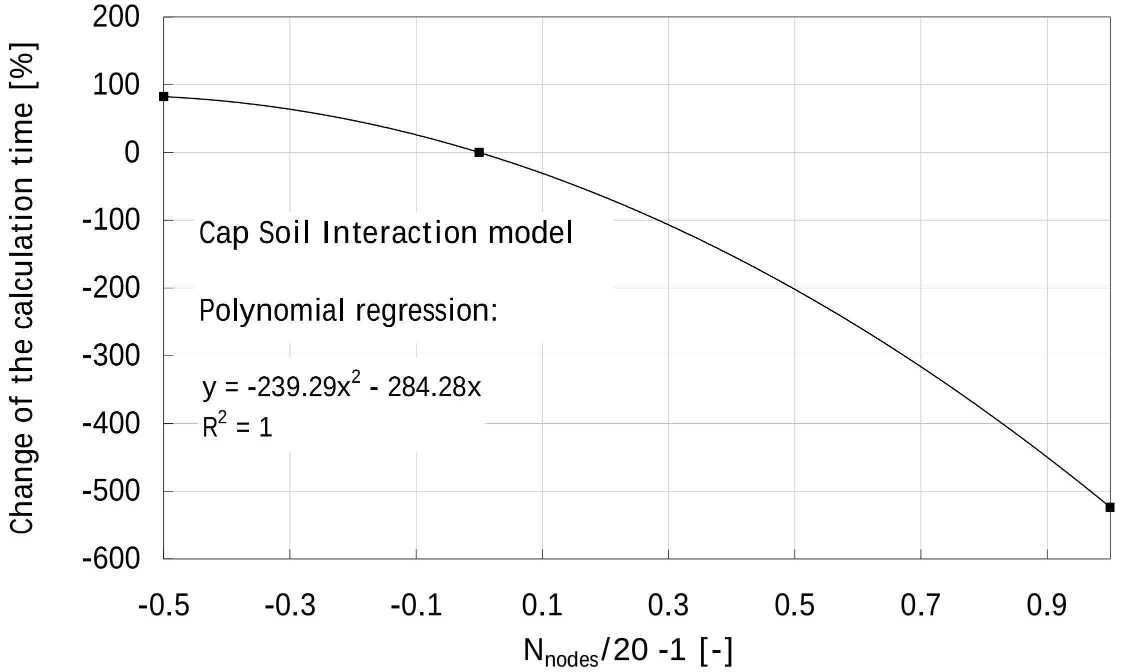

Figure 26 – Cap Soil Interaction model – Change of the calculation time vs. multiplication factor of the number of nodes

6 Model Cap Layered Soil Interaction (FEM)

6.1 Cap Soil Layered Interaction – 'Reference case'

The case used as reference for the Cap Soil Layered Interaction model is the same as for the Cap Soil Interaction model. For the soil interaction behaviour of the Peat, a Young's modulus of 100000 kN/m^2 and a Poisson ratio of 0.2 are used.

6.2 Parametric study of influence

First, a reference calculation is performed using the 'Reference case'. Then, the influence of several parameters is investigated:

- Influence of the pile density
- Influence of the type of pile
- Influence of the numbers of layers
- Influence of the cap loading
- Influence of the number of load-steps
- Influence of the required accuracy
- Influence of the pile/ cap connection
- Influence of the number of nodes along the pile

For each influencing parameter, at least three calculations are performed for three different number of piles (16, 25 and 36 piles) and the calculation time is compared to the 'Reference case' for those three cases. If the average relative error is more than 5%, then the parameter is considered as influencing. If so, additional calculations will be performed for a larger number of piles. If not so, the parameter will be considered as not influencing.

6.2.1 Cap Soil Interaction – Results of the 'Reference case'

The number of piles varies from 4 to 100 (i.e. 10 × 10). More piles could be inputted in D-PILE GROUP however, the calculation time becomes too long (8 hours for 100 piles). Results of the calculation time as a function of the number of piles are given in the table below and also graphically represented, showing a power regression.

Table 34: Cap Soil Layered Interaction model – Influence of the number of piles on the calculation time

Number of piles [-]	Calculation time [sec]		Ratio Cap Soil Layered/ Cap Soil [-]
	Cap Soil Layered	Cap Soil	
4	4	3	1.33
9	27	26	1.04
16	115	121	0.95
25	434	437	0.99
36	1267	1296	0.98
49	3156	3295	0.96
64	7135	7427	0.96
81	15553	15002	1.04
100	28806	28260	1.02

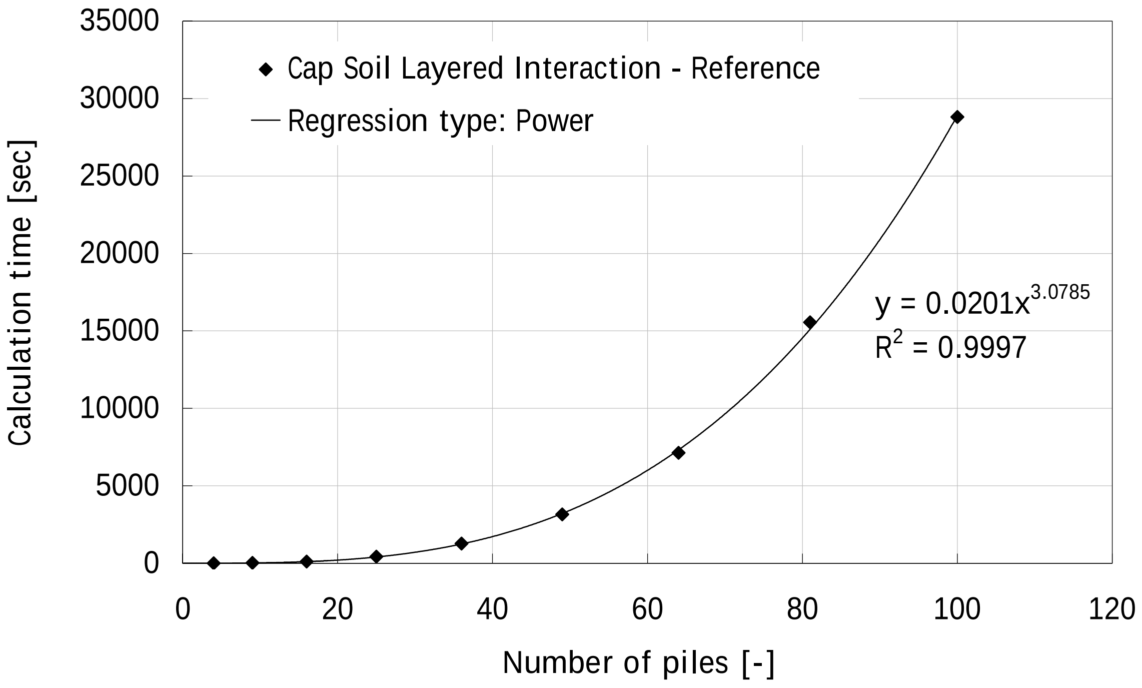

Figure 27 – Cap Soil Layered Interaction model – Calculation time vs. number of piles for the Reference case

A comparison with the results found for Cap Soil Interaction model is presented in the figure below, using a logarithmic scale and the same slope as the Cap Soil Layered Interaction model. As a conclusion, the calculation time with Cap Soil Layered Interaction model is 86 times longer than with Cap Soil Interaction model.

7 Model Dynamic (Ducbots)

The case used as reference for the Dynamic model is the same as Tutorial 7 of the user manual.

The number of piles varies from 4 to 400 (i.e. 20 × 20). More piles could be inputted in D-PILE GROUP however, the calculation time becomes too long (69 hours for 400 piles). Results of the calculation time as a function of the number of piles are given in the table below and also graphically represented, showing a power regression.

Table 35: Dynamic model – Influence of the number of piles on the calculation time

Number of piles [-]	Calculation time [sec]		Ratio Dynamic/ Cap [-]
	Dynamic	Cap	
4	18		
9	47	3	15.67
16	108		
25	232	16	14.50
49	923	70	13.19
81	3074		
144	13828		
225	47537	417	12.42
400	248983	1121	12.49

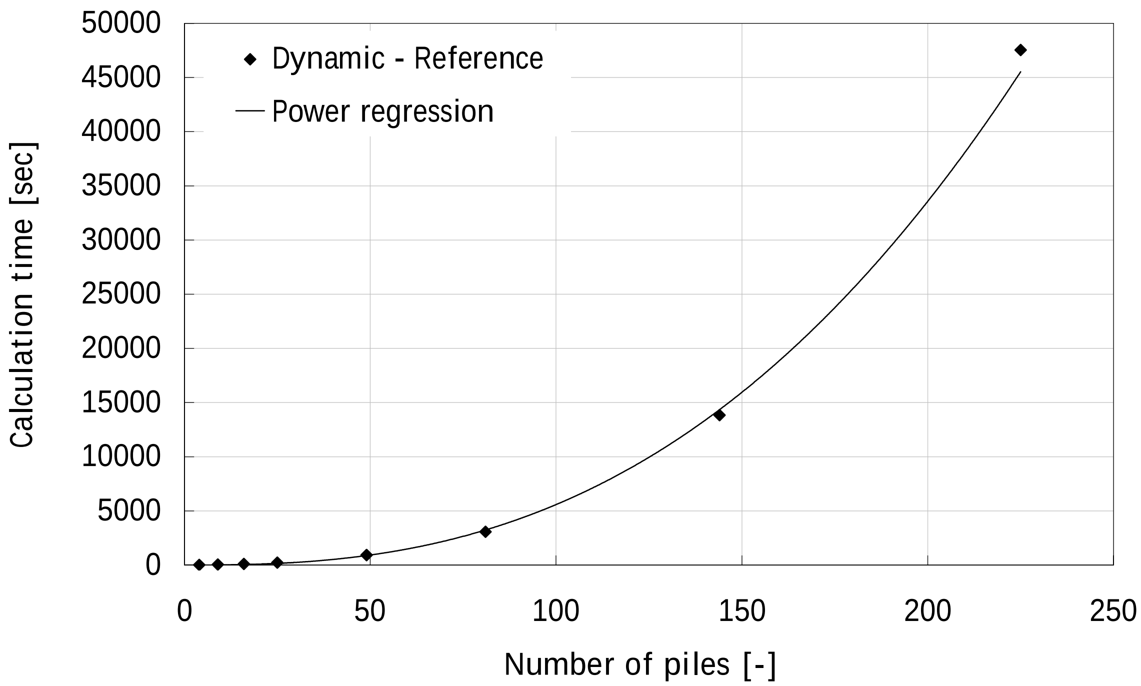

Figure 28 – Cap Soil Layered Interaction model – Calculation time vs. number of piles for the Reference case

A comparison with the results found for Cap model is presented in Figure *29*, using a logarithmic scale and the same slope as the Dynamic model. As a conclusion, the calculation time with Dynamic model is 11 times longer than with Cap model.

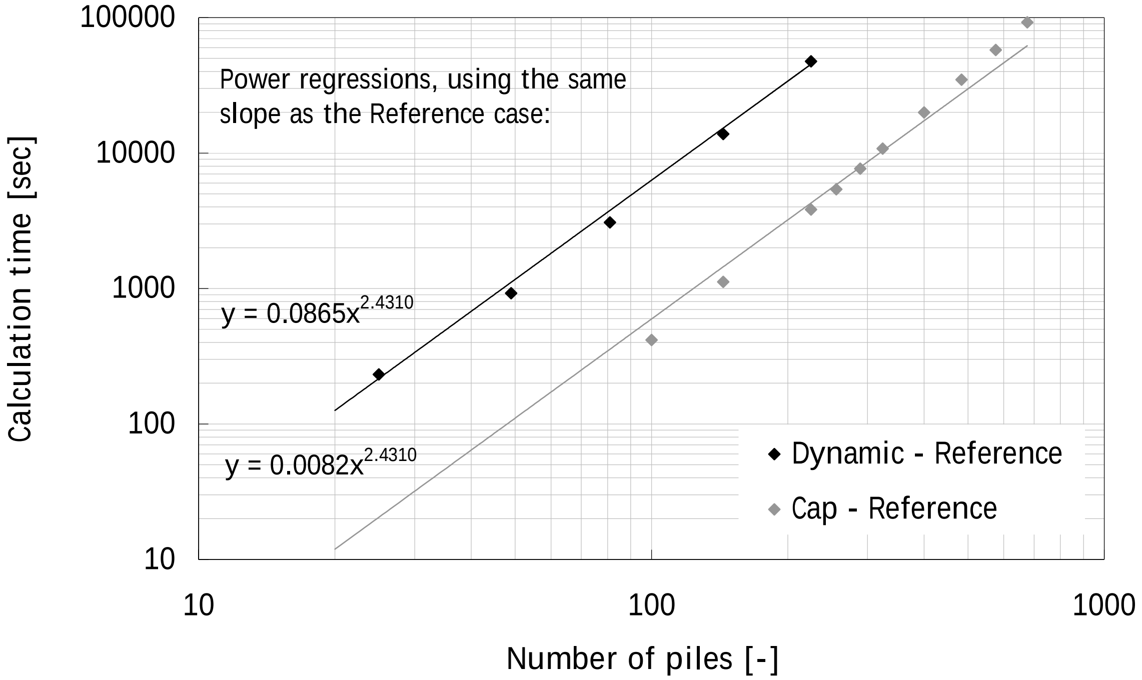

Figure 29 – Reference case – Comparison between Dynamic and Cap models

8 Conclusion

For a given project, the calculation time with all models is a power function of the number of piles.

The calculation time depends on the selected model:

- Calculation with Plasti-Poulos model is 20 times longer than with Poulos;
- Calculation with Cap Interaction model is 176 times longer than with Plasti-Poulos;
- Calculation with Cap Soil Interaction model is 86 times longer than with Cap Interaction;
- Calculation with Cap Soil Layered Interaction model is as longer as with the Cap Soil Interaction model;
- Calculation with Dynamic model is 11 times longer than with Cap Interaction.

Different parameters can influence this calculation time, among other things:

- the type of connection between the cap and the pile
- the number of nodes
- the number of load or time-steps
- the required accuracy
- the number of layers
- the type of cap loading
- the type of pile.