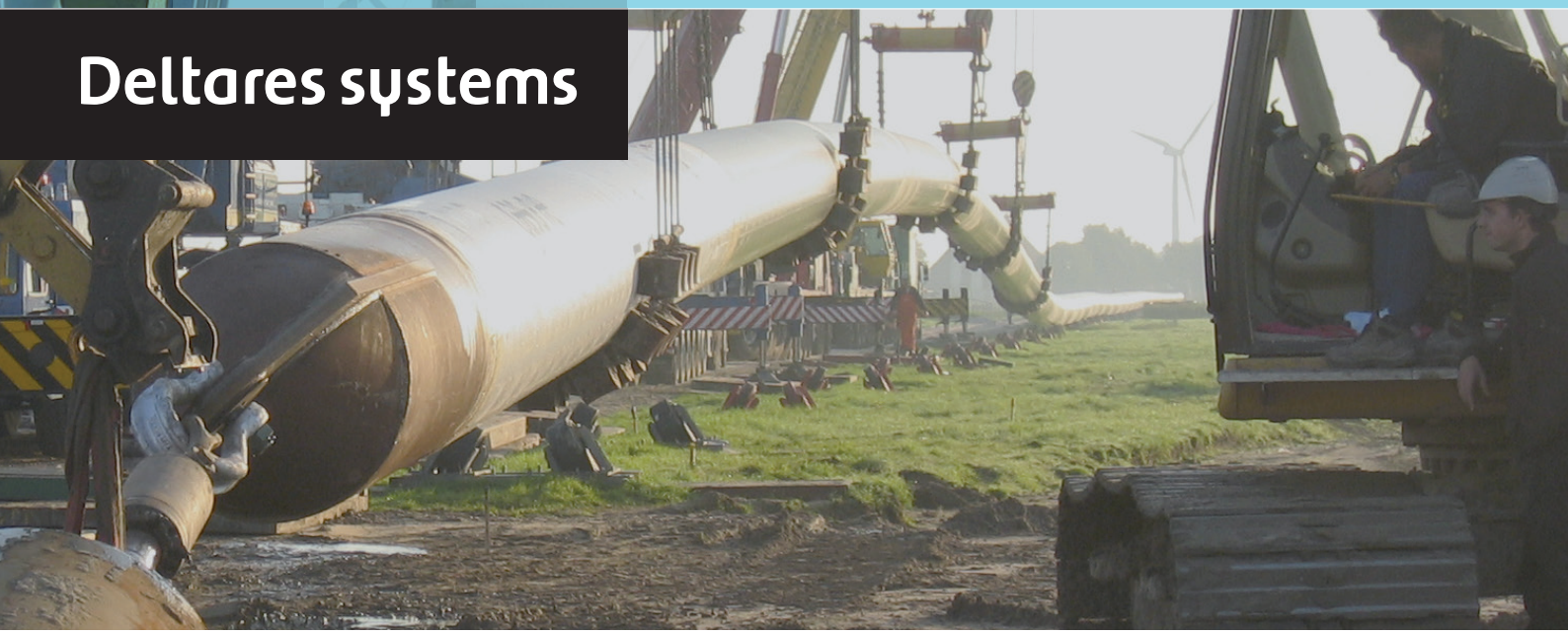
Design of pipeline installation

D-Geo Pipeline

Deltares systems



Deltares

Enabling Delta Life

Verification Report

D-GEO PIPELINE

Design of pipeline installation

Verification Report

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Contents

List of Figures

List of Tables

Introduction

Deltares Systems commitment to quality control and quality assurance has leaded them to develop a formal and extensive procedure to verify the correct working of all of their geotechnical engineering tools. An extensive range of benchmark checks have been developed to check the correct functioning of each tool. During product development these checks are run on a regular basis to verify the improved product. These benchmark checks are provided in the following sections, to allow the user to overview the checking procedure and verify for themselves the correct functioning of D-GEO PIPELINE.

The benchmarks are subdivided into five separate groups as described below.

- **Group 1 [chapter 1] – Benchmarks from literature (exact solution)**
  Simple benchmarks for which an exact analytical result is available from literature.
- **Group 2 [chapter 2] – Benchmarks from literature (approximate solution)**
  More complex benchmarks described in literature for which an approximate solution is known.
- **Group 3 [chapter 3] – Benchmarks from spread sheets**
  Benchmarks which test program features specific to MSheet.
- **Group 4 [chapter 4] – Benchmarks generated by D-GEO PIPELINE**
  Benchmarks for which the reference results are generated using D-GEO PIPELINE.
- **Group 5 [chapter 5] – Benchmarks compared with other programs**
  Benchmarks for which the results of D-GEO PIPELINE are compared with the results of other programs.

The number of benchmarks in group 1 may grow in the future. The benchmarks in this chapter are well documented in literature. There are no exact solutions available for these problems, however in the literature estimated results are available. When verifying the program, the results should be close to the results found in the literature.

The number of benchmarks in group 2 will grow as new versions of the program are released. These benchmarks are designed so that (new) features specific to the program can be verified. The benchmarks are kept as simple as possible so that only one specific feature is verified from one benchmark to the next.

As much as software developers would wish they could, it is impossible to prove the correctness of any non-trivial program. Re-calculating all the benchmarks in this report, and making sure the results are as they should be, proves to some degree that the program works as it should. Nevertheless, there will always be combinations of input values that will cause the program to crash or to produce wrong results. Hopefully by using the verification procedure the number of ways this can occur will be limited.

The benchmarks are all described in sufficient detail for reproduction to be possible at any time. The results are presented in text format with each benchmark description. The results in graphic format are available in the appendix, together with a copy of a part of the output file. This information is enough to be able to make the calculation. For each benchmark at least one picture is presented which shows the relevant results.

The different benchmarks from literature with an exact solution (group 1) are described in the following paragraphs.

1 Group 1: Benchmarks from literature (exact solution)

1.1 Soil type and displacement at maximal friction (Micro-tunneling and Trenching)

1.1.1 Description

This benchmark checks the classification of the soil type and the displacement at maximal friction associated to each soil type. Many combinations of parameters c and φ are simulated as shown in Table 1.1.

Table 1.1: *Material properties of the different layers (benchmark 1-1)*

Vertical nr.	Material description	c [kPa]	φ [°]	Friction displac. [mm]	Global soil type
1	Dense sand 1	0.2	32.6	2	Sand
2	Dense sand 2	0.5	40	2	Sand
3	Stiff clay 1	3	35	3	Clay
4	Medium dense sand 1	0.3	30.1	4	Sand
5	Medium dense sand 2	0.5	32	4	Sand
6	Stiff clay 2	1	32.5	3	Clay
7	Loose sand 1	0.1	25.1	7	Sand
8	Loose sand 2	1	26	7	Sand
9	Stiff sandy clay 1	5	27	5	Clay
10	Stiff sandy clay 2	10	29	3	Clay
11	Stiff clay 3	35	30	3	Clay
12	Clayey sand 1	4	22.6	7	Sand
13	Clayey sand 2	5	23	7	Sand
14	Stiff sandy clay 3	12	25	3	Clay
15	Medium stiff clay 1	6	20.1	5	Clay
16	Medium stiff clay 2	10	21	5	Clay
17	Stiff clay 4	15	22.5	4	Clay
18	Soft clay 1	4.9	17.1	8	Clay
19	Soft clay 2	5	18	8	Clay
20	Medium stiff clay 3	5.3	19	5	Clay
21	Stiff clay 5	10	20	5	Clay
22	Organic clay	15	17	10	Peat
23	Peat	30	14	13	Peat

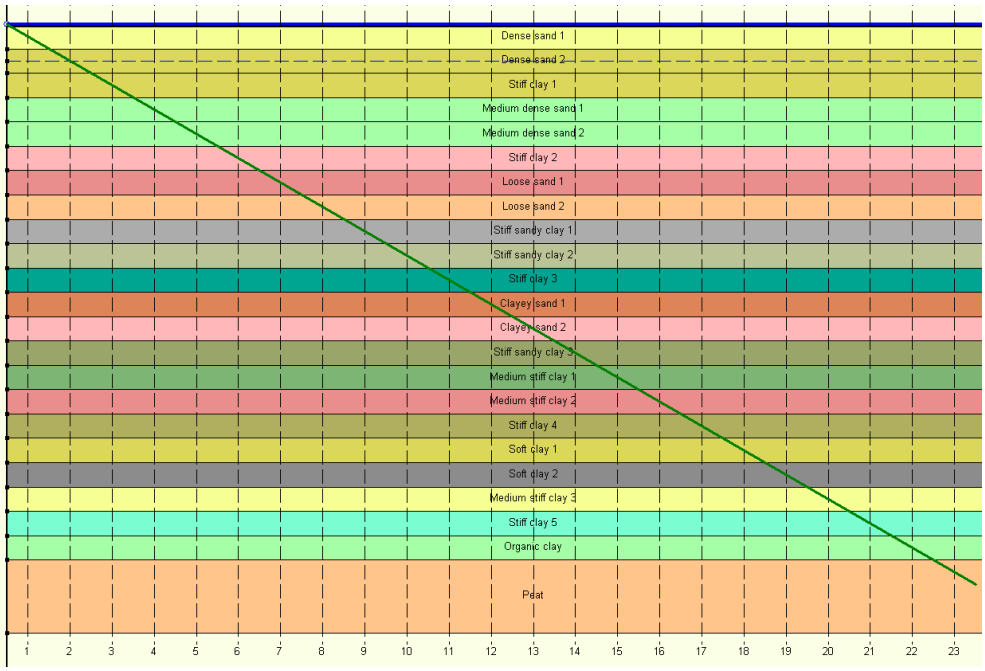

Figure 1.1: *Geometry of benchmark 1-1a (Construction in Trench)*

1.1.2 Benchmark results

The displacement necessary to develop the maximal axial friction along the pipeline and the classification of global soil types are determined using Table 1.2.

Table 1.2: *Displacement at maximal friction and classification of the soil type*

Soil type	**Global soil type**	φ	***c***	**Displacement**
		[°]	[kN/m^2]	[mm]
Dense sand	Sand	$\varphi > 32.5$	$c \leq 0.5$	1-3
Medium dense sand	Sand	$30 < \varphi \leq 32.5$	$c \leq 0.5$	3-5
Medium dense sand	Sand	$\varphi > 30$	$c > 0.5$	3-5
Loose sand	Sand	$25 < \varphi \leq 30$	$c \leq 1$	5-8
Stiff sandy clay	Clay	$25 < \varphi \leq 30$	$c > 1$	4-6
Stiff sandy clay	Clay	$22.5 < \varphi$ 25	$c > 5$	2-4
Clayey sand	Sand	$22.5 < \varphi \leq 25$	$c \leq 5$	5-8
Stiff clay	Clay	$20 < \varphi \leq 22.5$	$c > 10$	2-4
Medium stiff clay	Clay	$20 < \varphi \leq 22.5$	$c \leq 10$	4-6
Stiff clay	Clay	$17 < \varphi \leq 20$	$c > 10$	2-4
Medium stiff clay	Clay	$17 < \varphi \leq 20$	$5 < c \leq 10$	4-6
Soft clay	Clay	$17 < \varphi \leq 20$	$c \leq 5$	6-10
Peat / organic clay	Peat	$\varphi \leq 17$		10-15

The *Construction in trench* model (bm1-1a) and the *Micro-tunneling* model (bm1-1b) are checked. Benchmark results are presented in both tables below.

1.1.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 1.3: *Results of benchmark 1-1a, Global soil type for Construction in Trench*

Vertical nr.	**Benchmark**	**D-GEO PIPELINE**	**Result**
1	Sand	Sand	OK
2	Sand	Sand	OK
3	Clay	Clay	OK
4	Sand	Sand	OK
5	Sand	Sand	OK
6	Clay	Clay	OK
7	Sand	Sand	OK
8	Sand	Sand	OK
9	Clay	Clay	OK
10	Clay	Clay	OK
11	Clay	Clay	OK
12	Sand	Sand	OK
13	Sand	Sand	OK
14	Clay	Clay	OK
15	Clay	Clay	OK
16	Clay	Clay	OK
17	Clay	Clay	OK
18	Clay	Clay	OK
19	Clay	Clay	OK
20	Clay	Clay	OK
21	Clay	Clay	OK
22	Peat	Peat	OK
23	Peat	Peat	OK

Table 1.4: *Results of benchmark 1-1a, Maximal displacement for Construction in Trench*

Vertical nr.	**Benchmark** [mm]	**D-GEO PIPELINE** [mm]	**Rel. error** [%]
1	2	2	0.00
2	2	2	0.00
3	3	3	0.00
4	4	4	0.00
5	4	4	0.00
6	3	3	0.00
7	7	7	0.00
8	7	7	0.00
9	5	5	0.00
10	3	3	0.00
11	3	3	0.00
12	7	7	0.00
13	7	7	0.00
14	3	3	0.00
15	5	5	0.00
16	5	5	0.00
17	4	4	0.00
18	8	8	0.00
19	8	8	0.00
20	5	5	0.00
21	5	5	0.00
22	10	10	0.00
23	13	13	0.00

Table 1.5: *Results of benchmark 1-1b, Global soil type for Micro Tunneling*

Vertical nr.	**Benchmark**	**D-GEO PIPELINE**	**Error**
1	Sand	Sand	OK
2	Sand	Sand	OK
3	Clay	Clay	OK
4	Sand	Sand	OK
5	Sand	Sand	OK
6	Clay	Clay	OK
7	Sand	Sand	OK
8	Sand	Sand	OK
9	Clay	Clay	OK
10	Clay	Clay	OK
11	Clay	Clay	OK
12	Sand	Sand	OK
13	Sand	Sand	OK
14	Clay	Clay	OK
15	Clay	Clay	OK
16	Clay	Clay	OK
17	Clay	Clay	OK
18	Clay	Clay	OK
19	Clay	Clay	OK
20	Clay	Clay	OK
21	Clay	Clay	OK
22	Peat	Peat	OK
23	Peat	Peat	OK

Table 1.6: *Results of benchmark 1-1b, Maximal displacement for Micro Tunneling*

Vertical nr.	**Benchmark** [mm]	**D-GEO PIPELINE** [mm]	**Rel. error** [%]
1	2	2	0.00
2	2	2	0.00
3	3	3	0.00
4	4	4	0.00
5	4	4	0.00
6	3	3	0.00
7	7	7	0.00
8	7	7	0.00
9	5	5	0.00
10	3	3	0.00
11	3	3	0.00
12	7	7	0.00
13	7	7	0.00
14	3	3	0.00
15	5	5	0.00
16	5	5	0.00
17	4	4	0.00
18	8	8	0.00
19	8	8	0.00
20	5	5	0.00
21	5	5	0.00
22	10	10	0.00
23	13	13	0.00

Use D-GEO PIPELINE input files bm1-1a.dri and bm1-1b.dri to run this benchmark.

2 Group 2: Benchmarks from literature (approximate solution)

The different benchmarks from literature for which an approximate solution is known are described in this chapter. Currently, no benchmarks are available.

3 Group 3: Benchmarks from spreadsheets

The benchmarks in this chapter (group 3) check if the output of D-GEO PIPELINE is according to the formula's given in the User Manual of D-GEO PIPELINE [Deltares] using spreadsheets. Those formula's are based on the Dutch standards NEN 3650-1, NEN 3650-2, NEN 3650-3 and NEN 3651 (NEN, 2012a,b,c,d).

3.1 HDD with 2D geometry – Steel pipe in two compressible undrained layers

3.1.1 Description

The pipe is constructed in two compressible undrained layers (clay and sand) with the characteristics given in Table 3.1. The boundaries between compressible/incompressible layers and drained/undrained layers are situated at the bottom of the sand layer. The ground level is at depth Z = 0 m and the phreatic line is at depth Z = -3 m. The steel pipe properties are given in Table 3.2. Calculations are performed for 8 verticals with L coordinates of 20, 50, 100, 200, 350, 500, 650 and 680 m.

The configuration of the pipeline is given by:

X_{left}	10 m	X-coordinate of the left entry point
X_{right}	690 m	X-coordinate of the right exit point
φ_{left}	13 deg	Left angle of the pipe
φ_{right}	15 deg	Right angle of the pipe
Z_{lowest}	-50 m	Lowest level of the pipe
R_{left}	600 m	Bending radius of the pipe at the left side
R_{right}	800 m	Bending radius of the pipe at the right side
R_{rol}	1000 m	Bending radius in pipe string (on rollers)

Table 3.1: *Soil material properties (bm3-1)*

			Sand	Clay
Bottom depth of the layer	Z_{lowest}	[m]	-60	-15
Unit weight above phreatic level	γ_{unsat}	[kN/m^3]	18	14
Unit weight below phreatic level	γ_{sat}	[kN/m^3]	20	16
Cohesion	c	[kN/m^2]	0.2	5
Friction angle	φ	[deg]	30	22.5
Undrained cohesion at the top	$c_{\text{u;top}}$	[kN/m^2]	0.2	25
Undrained cohesion at the bottom	$c_{\text{u;bot}}$	[kN/m^2]	0.5	30
Young modulus at the top	E_{top}	[kN/m^2]	20000	1500
Young modulus at the top	E_{bot}	[kN/m^2]	25000	2000
Poisson ratio	ν	[-]	0.45	0.4

Table 3.2: *Pipe material data (bm3-1)*

Material			Steel
Negative wall thickness tolerance	δt	[%]	15
Yield strength	R_{eb}	[N/mm^2]	235
Partial material factor	γ_m	[-]	1.1
Partial material factor for test pressure	$\gamma_{m;test}$	[-]	1
Young's modulus	E_b	[N/mm^2]	205800
Outer diameter	D_0	[m]	0.8
Nominal wall thickness	d_n	[mm]	19
Unit weight	γ_b	[kN/m^3]	78.5
Design pressure	p_d	[kN/m^2]	600
Test pressure	p_t	[kN/m^2]	834
Temperature variation	Δt	[°]	10

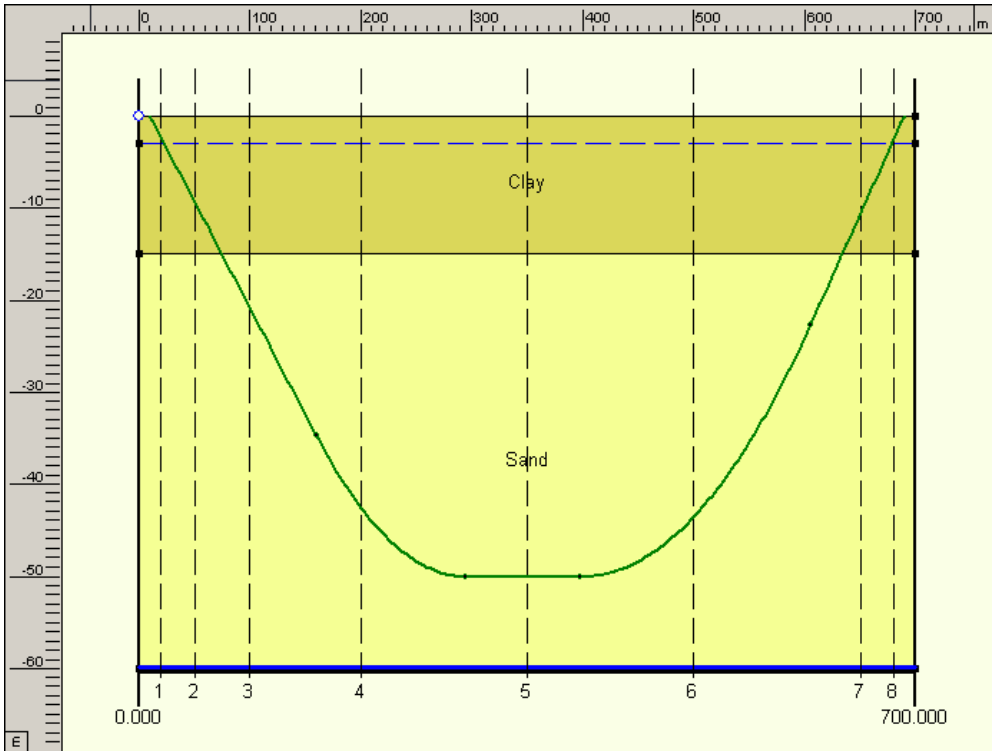

Figure 3.1: *2D Geometry of benchmark 3-1 (steel pipeline in two compressible undrained layers)*

3.1.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Soil mechanical data

The soil mechanical data's are determined using the formulas given in chapter *Calculation of soil mechanical data* in the Background section of the User Manual of D-GEO PIPELINE. The maximal axial friction between the pipe and the drilling fluid is constant along the pipeline and equal to f_2 = 50 N/m^2. The displacement necessary to develop the maximal axial friction along the pipeline is estimated between 6 and 9 mm (= 7.5 mm).

Minimum drilling fluid pressures

For the minimum drilling fluid pressures, calculations are performed during the three stages of the drilling process using the formulas given in paragraph *"Minimum required drilling fluid pressure"* in the Background section of the User Manual of D-GEO PIPELINE [Deltares]. The minimum required pressure *dp*/*dz* is the optimal value for which the calculated flow rate Q is equal to the requested flow rate Q_{req} (necessary to initiate flow of drilling fluid). Calculations are performed in an Excel spreadsheet using the solver option and lead to the values of dp/dz given in Table 3.3.

Table 3.3: *Analytical results for the calculation of dp/dz for the three stages*

		Pilot	Pre-ream	Pull back
Pipe diameter	[m]	0.114	0.5	0.8
Hole radius	[m]	0.1	0.3	0.45
Circulation loss factor f_{loss}	[-]	0.3	0.2	0.2
Annular back flow rate Q_{ann}	[m^3/s]	0.0025	0.0067	0.0033
Request back flow rate Q_{req}	[m^3/s]	0.00175	0.00536	0.00264
Minimum required pressure dp/dz	[kN/m^3]	0.63631	0.56048	0.56018

Maximum drilling fluid pressures

For the maximum drilling fluid pressures in undrained conditions, calculations are performed using the formulas given in paragraph *Maximum required drilling fluid pressure* in the Background section of the User Manual of D-GEO PIPELINE. Analytical results are given in the table below.

Table 3.4: *Analytical results for the calculation of the maximum drilling fluid pressures*

Vert.	u	0.9 p_{limit}	p_{pilot}	p_{preream}	p_{back}	p_{pilot}	p_{preream}	p_{back}
plastic zone related to :			deformation bore hole			soil cover		
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]
1	0	88.6	95.29	80.21	69.47	95.29	80.21	69.47
2	62.35	122.71	136.09	134.22	131.85	136.09	134.22	131.85
3	177.78	107.92	119.49	117.92	117.01	119.49	117.92	117.01
4	394.42	222.39	246.97	246.52	246.25	246.97	246.52	246.25
5	470	264.87	294.21	293.81	293.56	294.21	293.81	293.56
6	404.81	228.21	253.45	253	252.74	253.45	253	252.74
7	77.18	129.29	143.47	142.02	140.14	143.47	142.02	140.14
8	0	91.95	99.75	87.08	77.24	99.75	87.08	77.24

Strength calculation

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter *"Strength pipeline calculation"* in the Background section of the User Manual of D-GEO PIPELINE.

The length of the pipe in the borehole at the characteristic points (Figure 3-2) is:
$L_{\text{A}} = 0$ m
$L_{\text{B}} = L_{\text{A}} + |Z_{\text{lowest}} + R_{\text{left}} \times (1 - \cos\varphi_{\text{left}})| \,/\, \sin\varphi_{\text{left}} = 153.909$ m
$L_{\text{C}} = L_{\text{B}} + \varphi_{\text{left}} \times R_{\text{left}} = 290.045$ m
$L_{\text{d}} = L_{\text{C}} + X_{\text{right}} - |Z_{\text{lowest}} + R_{\text{right}}\,(1 - \cos\varphi_{\text{right}})| \,/\, \tan\varphi_{\text{right}} - R_{\text{right}} \times \sin\varphi_{\text{right}}$
$- X_{\text{left}} - |Z_{\text{lowest}} + R_{\text{left}} \times (1 - \cos\varphi_{\text{left}})| \,/\, \tan\varphi_{\text{left}} - R_{\text{left}} \times \sin\varphi_{\text{left}} = 393.185$ m
$L_{\text{E}} = L_{\text{d}} + \varphi_{\text{right}} \times R_{\text{right}} = 602.625$ m

$$L_F = L_E + |Z_{lowest} + R_{right} \times (1 - \cos \varphi_{right})| \,/\, \sin \varphi_{right} = 690.488 \text{ m}$$

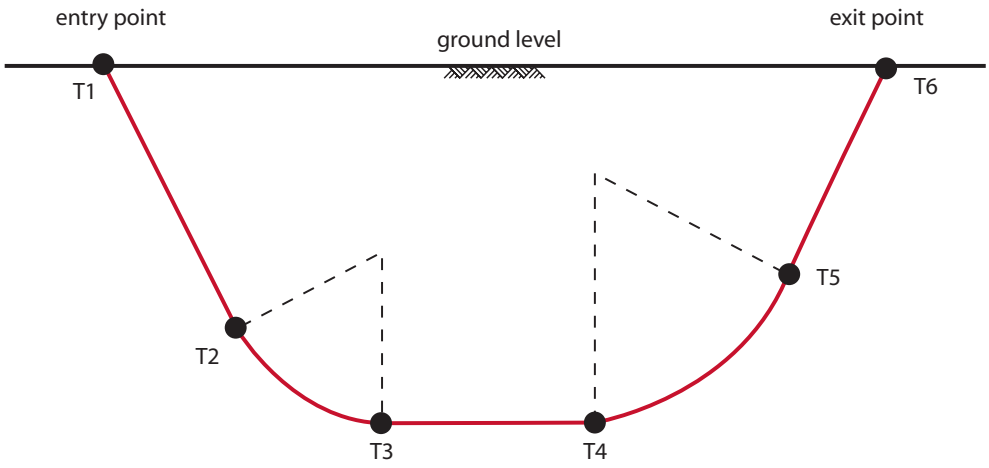

Figure 3.2: *Locations of the characteristic points T1 to T6*

Hereafter are some intermediate results used for the pulling force and the strength calculations:

Factor of friction pipe-roller	f_1	0.1	[-]
Friction pipe-mud	f_2	0.00005	[N/mm^2]
Factor of friction pipe-soil	f_3	0.2	[-]
Load factor - Design pressure	f_{pd}	1.25	[-]
Load factor - Design pressure (combination)	$f_{pd;comb}$	1.15	[-]
Load factor - Test pressure	f_{pt}	1.1	[-]
Load factor - Installation	$f_{install}$	1.1	[-]
Load factor - Soil load Qn	f_{Qn1}	1.5	[-]
Load factor - Temperature	f_{temp}	1.1	[-]
Contingency factor - E-modulus	f_E	1.25	[-]
Contingency factor - Pulling force	f_{pull}	1.4	[-]
Contingency factor - Modulus of subgrade reaction	f_{kv}	1.6	[-]
Contingency factor - Soil load Qn	f_{Qn2}	1.1	[-]
Contingency factor - Bending moment	f_M	1.27	[-]
Contingency factor - Bending radius	f_R	1.1	[-]
Contingency factor - Pressure borehole	$f_{press;bore}$	1.1	[-]
Effective weight of pipe	g_{eff}	1.414	[N/mm]
Weight of pipeline (incl. filling)	g_{fill}	0.456	[N/mm]
Uplift force	g_{upw}	5.529	[N/mm]
Moment coefficient indirect bottom	k_b'	0.083	[-]
Moment coefficient indirect top	k_t'	0.061	[-]
Moment coefficient direct bottom	k_b	0.138	[-]
Moment coefficient direct top	k_t	0.131	[-]
Direct deflection factor	k_y	0.089	[-]
Indirect deflection factor	k_y'	0.048	[-]
Part of pipe filled with water during pull back	P_{water}	10	[%]
Cross sections of the pipe	A	39769.979	[mm^2]
	A_{trek}	46618.093	[mm^2]

	A_{inw}	456036.731	[mm^2]
Minimal wall thickness	$d_{n;min}$	16.15	[mm]
Outer radius of the pipeline	r_e	400	[mm]
Inner radius of the pipeline	r_i	381	[mm]
Average radius of the pipeline	r_g	390.5	[mm]
Moment of inertia of the pipe	I_b	3556505999	[mm^4]
Moment of inertia of the wall	I_w	571.583	[mm^3]
Pipe resisting moment	W_b	8891265	[mm^{4}m]
Wall resisting moment	W_w	60.167	[mm^{3}m]
Unit weight of drilling fluid	$\gamma_{drill\ fluid}$	11	[kN/m^3]
Maximum modulus of subgrade reaction	$k_{v;max}$	30945.502	[kN/m^3]
Maximum neutral vertical soil load	$q_{v;n;r;max}$	184.15	[kN/m^2]
Maximum corrected reduced soil load	q_n	303.847	[kN/m^2]
Maximum neutral horizontal soil load	$q_{h;n;r}$	136.488	[kN/m^2]
Soil reaction - Left curve	$q_{r;left}$	49.727	[kN/m^2]
Soil reaction - Right curve	$q_{r;right}$	37.295	[kN/m^2]
Soil reaction - Left curve (long term)	$q_{r;left}$	n.a.	[kN/m^2]
Soil reaction - Right curve (long term)	$q_{r;right}$	n.a.	[kN/m^2]
Characteristic stiffness pipeline-soil	λ	0.0003032	[mm^{-1}]
Characteristic stiffness pipeline-soil (long term)	λ_{long}	n.a.	[mm^{-1}]

The total pulling force is the contribution of five components. Results are given in Table 3-5.

Table 3.6: *Results of benchmark 3-01, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	284	0	284	0.00	0.00
T2	154	284	154	284	0.00	0.00
T3	290	468	290	468	0.00	0.00
T4	393	468	393	468	0.00	0.00
T5	603	622	603	622	0.00	0.00
T6	690	622	690	622	0.00	0.00
Max. rep. pulling force	-	5187	-	5187	-	0.00

The maximum combined stress at the top or the bottom, and inside or outside the pipe is calculated in the tables below and used for checking the calculated stresses.

Table 3.7: *Set for calculation of the maximum stresses for load combination 1A*

	Top outside	Top inside	Bottom inside	Bottom outside
σ_x [N/mm^2]	115.5	115.5	137.51	137.51
σ_y [N/mm^2]	0	0	0	0
σ_V [N/mm^2]	115.5	115.5	137.51	137.51

Table 3.8: *Set for calculation of the maximum stresses for load combination 1B*

	Top outside	Top inside	Bottom inside	Bottom outside
σ_x [N/mm^2]	186.75	186.75	234.92	234.92
σ_y [N/mm^2]	-15.81	15.81	21.51	-21.51
σ_V [N/mm^2]	195.14	179.37	224.94	246.38

Table 3.9: *Set for calculation of the maximum stresses for load combination 3*

	Top outside	Top inside	Bottom inside	Bottom outside
$\sigma_{x;2}$ [N/mm^2]	0	0	0	0
$\sigma_{y;2}$ [N/mm^2]	-207.43	207.43	218.51	-218.51
$\sigma_{V;2}$ [N/mm^2]	207.43	207.43	218.51	218.51
$\sigma_{x;3}$ [N/mm^2]	-210.84	-210.84	210.84	210.84
$\sigma_{y;3}$ [N/mm^2]	0	0	0	0
$\sigma_{V;3}$ [N/mm^2]	210.84	210.84	210.84	210.84
$\sigma_{x;4}$ [N/mm^2]	-210.84	-210.84	210.84	210.84
$\sigma_{y;4}$ [N/mm^2]	-223.23	223.23	240.02	-240.02
$\sigma_{V;4}$ [N/mm^2]	217.3	375.97	226.84	390.72

Table 3.10: *Set for calculation of the maximum stresses for load combination 4*

	Top outside	Top inside	Bottom inside	Bottom outside
$\sigma_{x;1}$ [N/mm^2]	8.37	8.37	8.37	8.37
$\sigma_{y;1}$ [N/mm^2]	16.74	16.74	16.74	16.74
$\sigma_{V;1}$ [N/mm^2]	14.5	14.5	14.5	14.5
$\sigma_{x;2}$ [N/mm^2]	8.37	8.37	8.37	8.37
$\sigma_{y;2}$ [N/mm^2]	-179.93	213.42	223.93	-190.44
$\sigma_{V;2}$ [N/mm^2]	184.26	209.36	219.86	194.76
$\sigma_{x;3}$ [N/mm^2]	-202.46	-202.46	219.21	219.21
$\sigma_{y;3}$ [N/mm^2]	16.74	16.74	16.74	16.74
$\sigma_{V;3}$ [N/mm^2]	211.33	211.33	211.33	211.33
$\sigma_{x;4}$ [N/mm^2]	-202.46	-202.46	219.21	219.21
$\sigma_{y;4}$ [N/mm^2]	-195.29	228.78	244.82	-211.33
$\sigma_{V;4}$ [N/mm^2]	198.97	373.7	233.07	372.88

3.1.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.11: *Results of benchmark 3-01, Maximum allowable drilling fluid pressure (plastic zone related to deformation bore hole)*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	89	80	69	89	80	69	0.00	0.00	0.00
2	185	185	185	185	185	185	0.00	0.00	0.00
3	286	286	286	286	286	286	0.00	0.00	0.00
4	617	617	617	617	617	617	0.00	0.00	0.00
5	735	735	735	735	735	735	0.00	0.00	0.00
6	633	633	633	634	634	634	0.16	0.16	0.16
7	206	206	206	206	206	206	0.00	0.00	0.00
8	92	87	77	92	87	77	0.00	0.00	0.00

Table 3.12: *Results of benchmark 3-01, Maximum allowable drilling fluid pressure (plastic zone related to soil cover)*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	89	80	69	89	80	69	0.00	0.00	0.00
2	185	185	185	185	185	185	0.00	0.00	0.00
3	286	286	286	286	286	286	0.00	0.00	0.00
4	617	617	617	617	617	617	0.00	0.00	0.00
5	735	735	735	735	735	735	0.00	0.00	0.00
6	633	633	633	634	634	634	0.16	0.16	0.16
7	206	206	206	206	206	206	0.00	0.00	0.00
8	92	87	77	92	87	77	0.00	0.00	0.00

Table 3.13: *Results of benchmark 3-01, Minimum required drilling fluid pressure (from left to right)*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	32	31	31	32	31	31	0.00	0.00	0.00
2	128	125	125	129	125	125	0.78	0.00	0.00
3	287	280	280	290	281	281	1.03	0.36	0.36
4	591	576	576	597	578	577	1.01	0.35	0.17
5	770	743	743	780	747	745	1.28	0.54	0.27
6	794	602	588	808	608	590	1.73	0.99	0.34
7	531	144	141	551	145	142	3.63	0.69	0.7
8	462	36	35	483	36	35	4.35	0.00	0.00

Table 3.14: *Results of benchmark 3-01, Minimum required drilling fluid pressure (from right to left)*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	458	32	31	479	32	31	4.38	0.00	0.00
2	515	128	125	534	129	125	3.56	0.78	0.00
3	609	287	280	627	290	281	2.87	1.03	0.36
4	782	591	576	797	597	578	1.88	1.01	0.35
5	770	744	743	780	747	745	1.28	0.4	0.27
6	602	588	588	608	590	589	0.99	0.34	0.17
7	144	141	141	145	142	141	0.69	0.7	0.00
8	36	35	35	36	35	35	0.00	0.00	0.00

Table 3.15: *Results of benchmark 3-01, Equilibrium between drilling fluid pressure and pore pressure*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	Drilling fluid	Water	Safety	Drilling fluid	Water	Safety	Drilling fluid	Water	Safety
[-]	[kN/m^2]	[kN/m^2]	[-]	[kN/m^2]	[kN/m^2]	[-]	[%]	[%]	[%]
1	25.4	0	-	25.4	0		0.00	0.00	
2	101.58	62.35	1.63	101.58	62.35	1.63	0.00	0.00	0.00
3	228.56	177.78	1.29	228.56	177.78	1.29	0.00	0.00	0.00
4	466.86	394.42	1.18	466.86	394.42	1.18	0.00	0.00	0.00
5	550	470	1.17	550	470	1.17	0.00	0.00	0.00
6	478.29	404.81	1.18	478.29	404.81	1.18	0.00	0.00	0.00
7	117.9	77.18	1.53	117.9	77.18	1.53	0.00	0.00	0.00
8	29.47	0	-	29.47	0		0.00	0.00	

Table 3.16: *Results of benchmark 3-01, Vertical soil stresses*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	47	28	28	47	28	28	0.00	0.00	0.00
2	234	77	62	234	77	62	0.00	0.00	0.00
3	916	169	114	916	169	114	0.00	0.00	0.00
4	1656	385	178	1656	385	178	0.00	0.00	0.00
5	1887	461	184	1887	461	184	0.00	0.00	0.00
6	1688	396	179	1688	396	179	0.00	0.00	0.00
7	253	86	68	253	86	68	0.00	0.00	0.00
8	60	33	33	60	33	33	0.00	0.00	0.00

Table 3.17: *Results of benchmark 3-01, Neutral horizontal soil stress and bearing capacities*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$p_{h;n}$	$P_{v;e}$	$P_{h;e}$	$p_{h;n}$	$P_{v;e}$	$P_{h;e}$	$p_{h;n}$	$P_{v;e}$	$P_{h;e}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	21	508	105	21	508	105	0.00	0.00	0.00
2	46	1090	234	46	1090	234	0.00	0.00	0.00
3	84	4612	916	84	4612	916	0.00	0.00	0.00
4	132	10388	1656	132	10388	1656	0.00	0.00	0.00
5	136	12404	1887	136	12404	1887	0.00	0.00	0.00
6	133	10665	1688	133	10665	1688	0.00	0.00	0.00
7	50	1199	253	50	1199	253	0.00	0.00	0.00
8	24	568	121	24	568	122	0.00	0.00	0.82

Table 3.18: *Results of benchmark 3-01, Vertical and horizontal moduli of subgrade reaction*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h
[-]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[%]	[%]	[%]
1	797	865	606	797	865	606	0.00	0.00	0.00
2	904	992	695	904	992	695	0.00	0.00	0.00
3	12768	13121	9185	12768	13121	9185	0.00	0.00	0.00
4	14365	14720	10304	14365	14720	10304	0.00	0.00	0.00
5	14924	15280	10696	14924	15280	10696	0.00	0.00	0.00
6	14441	14797	10358	14441	14797	10358	0.00	0.00	0.00
7	931	1317	922	931	1317	922	0.00	0.00	0.00
8	800	872	611	800	872	611	0.00	0.00	0.00

Table 3.19: *Results of benchmark 3-01, Maximal axial friction and displacements*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}
[-]	[kN/m^2]	[mm]	[mm]	[kN/m^2]	[mm]	[mm]	[%]	[%]	[%]
1	0.05	5	8	0.05	5	8	0.00	0.00	0.00
2	0.05	10	8	0.05	10	8	0.00	0.00	0.00
3	0.05	20	8	0.05	20	8	0.00	0.00	0.00
4	0.05	40	8	0.05	40	8	0.00	0.00	0.00
5	0.05	80	8	0.05	80	8	0.00	0.00	0.00
6	0.05	60	8	0.05	60	8	0.00	0.00	0.00
7	0.05	50	8	0.05	50	8	0.00	0.00	0.00
8	0.05	35	8	0.05	35	8	0.00	0.00	0.00

Table 3.20: *Results of benchmark 3-01, Buoyancy control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	553	553	0.00
Weight of pipeline (incl. filling)	[kg/m]	412	412	0.00
Effective weight of pipe	[kg/m]	141	141	0.00

Table 3.21: *Results of benchmark 3-01, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	284	0	284	0.00	0.00
T2	154	284	154	284	0.00	0.00
T3	290	468	290	468	0.00	0.00
T4	393	468	393	468	0.00	0.00
T5	603	622	603	622	0.00	0.00
T6	690	622	690	622	0.00	0.00
Max. rep. pulling force	-	5187	-	5187	-	0.00

Table 3.22: *Results of benchmark 3-01, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	127	127	0.00
σ_t	[N/mm^2]	11	11	0.00
$\sigma_{a;max}$	[N/mm^2]	138	138	0.00
$\sigma_{V;max}$	[N/mm^2]	138	138	0.00

Table 3.23: *Results of benchmark 3-01, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	211	211	0.00
σ_t	[N/mm^2]	24	24	0.00
$\sigma_{a;max}$	[N/mm^2]	235	235	0.00
λ	[mm^{-1}]	0.000303	0.000303	0.00
q_r	[N/mm^2]	0.04973	0.04973	0.00
σ_{qr}	[N/mm^2]	22	22	0.00
$\sigma_{t;max}$	[N/mm^2]	22	22	0.00
$\sigma_{V;max}$	[N/mm^2]	246	246	0.00

Table 3.24: *Results of benchmark 3-01, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	18	18	0.00
σ_{px}	[N/mm^2]	9	9	0.00
σ_{ptest}	[N/mm^2]	22	22	0.00
σ_{pm}	[N/mm^2]	16	16	0.00

Table 3.25: *Results of benchmark 3-01, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	211	211	0.00
$\sigma_{a;max}$	[N/mm^2]	211	211	0.00
σ_{qr}	[N/mm^2]	22	22	0.00
σ_{qr}	[N/mm^2]	219	219	0.00
$\sigma_{t;max}$	[N/mm^2]	240	240	0.00
$\sigma_{V;max}$	[N/mm^2]	391	391	0.00

Table 3.26: *Results of benchmark 3-01, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	211	211	0.00
σ_{py}	[N/mm^2]	17	17	0.00
σ_{px}	[N/mm^2]	8	8	0.00
σ_{ptest}	[N/mm^2]	22	22	0.00
σ_{ptemp}	[N/mm^2]	26	26	0.00
$\sigma_{a;max}$	[N/mm^2]	219	219	0.00
σ_{qr}	[N/mm^2]	22	22	0.00
σ_{qr}	[N/mm^2]	219	219	0.00
$\sigma_{V;max}$	[N/mm^2]	374	374	0.00

Table 3.27: *Results of benchmark 3-01, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	235	235	0.00
σ_{py}	[N/mm^2]	213.64	213.64	0.00
σ_{pm}	[N/mm^2]	235	235	0.00
$\sigma_{V;max}$	[N/mm^2]	363.18	363.18	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.28: *Results of benchmark 3-01, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	6.7	6.7	0.00
Max. allowable	[mm]	136	136	0.00
Max. allow. (piggability)	[mm]	64	64	0.00

Table 3.29: *Results of benchmark 3-01, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Use D-GEO PIPELINE input file bm3-1.dri to run this benchmark.

3.2 HDD with 2D geometry – Vertical bearing capacity in homogeneous compressible undrained layer with φ = 0

3.2.1 Description

The same configuration as benchmark 3-1 (section 3.1) is used, except that both layers have the same properties:

Unit weight above phreatic level	[kN/m^3]	γ_{unsat}	14
Unit weight below phreatic level	[kN/m^3]	γ_{sat}	16
Cohesion	[kN/m^2]	c	5
Friction angle	[°]	φ	0

3.2.2 Analytical results

Analytical results for the ultimate vertical bearing capacity $P_{v;e}$ with φ = 0 are worked out in an Excel spreadsheet using the formula given in paragraph "Ultimate vertical bearing capacity" in the Background section of the User Manual of D-GEO PIPELINE. Intermediate results are given in the tables below.

Table 3.30: *Analytical results for the calculation of the vertical bearing capacity*

Vert.	L	Z	σ_V'	h_h	d_C	s_C	$P_{v;e}$
[-]	[m]	[m]	[kN/m^2]	[m]	[-]	[-]	[kN/m^2]
1	20	-2.309	32.322	2.309	0.513	0.02	68.156
2	50	-9.235	79.408	9.235	0.595	0.02	114.885
3	100	-20.778	148.669	20.778	0.613	0.02	181.123
4	200	-42.442	278.651	42.442	0.621	0.02	304.792
5	350	-50	324	50	0.622	0.02	347.901
6	500	-43.481	284.883	43.481	0.621	0.02	310.717
7	650	-10.718	88.308	10.718	0.6	0.02	123.447
8	680	-2.679	37.513	2.679	0.527	0.02	73.41

3.2.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.31: *Results of benchmark 3-02, Ultimate vertical bearing capacity*

Vert. nr.	**Benchmark**	**D-GEO PIPELINE**	**Relative error**
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]
1	68.16	68.16	0.00
2	114.88	114.88	0.00
3	181.12	181.12	0.00
4	304.79	304.79	0.00
5	347.9	347.9	0.00
6	310.72	310.72	0.00
7	123.45	123.45	0.00
8	73.41	73.41	0.00

Use D-GEO PIPELINE input file bm3-2.dri to run this benchmark.

3.3 HDD with 2D geometry – Polyethylene (PE 80) pipe in two compressible undrained layers

3.3.1 Description

The same data used for benchmark 3-1 (section 3.1) is used except that polyethylene is used as pipe material instead of steel as shown in Table 3.32.

Table 3.32: *Pipe material data (benchmark 3-3)*

Material	Polyethylene	PE 80
Young's modulus (long term)	$E_{\text{pipe;long}}$	200 N/mm^2
Young's modulus (short term)	$E_{\text{pipe;short}}$	1000 N/mm^2
Allowable strength (long term)	$R_{\text{e;long}}$	6.3 N/mm^2
Allowable strength (short term)	$R_{\text{e;short}}$	8 N/mm^2
Tensile factor	α	0.65
Outer diameter	D_0	0.8 m
Nominal wall thickness	d_{n}	47.4 mm
Unit weight	γ_{b}	9.54 kN/m^3
Design pressure	p_{d}	600 kN/m^2
Test pressure	p_{t}	834 kN/m^2
Temperature variation	Δt	10°

3.3.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Strength calculation

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter "Strength pipeline calculation" in the Background section of the User Manual of D-GEO PIPELINE. Intermediate results are given below.

Factor of friction pipe-roller	f_1	0.1	[-]
Friction pipe-mud	f_2	0.00005	[N/mm^2]
Factor of friction pipe-soil	f_3	0.2	[-]
Load factor - Design pressure	f_{pd}	n.a.	[-]
Load factor - Design pressure (combination)	$f_{\text{pd;comb}}$	n.a.	[-]
Load factor - Test pressure	f_{pt}	n.a.	[-]
Load factor - Installation	f_{install}	n.a.	[-]
Load factor - Soil load Qn	f_{Qn1}	n.a.	[-]
Load factor - Temperature	f_{temp}	n.a.	[-]
Contingency factor - E-modulus	f_{E}	1.25	[-]
Contingency factor - Pulling force	f_{pull}	1.4	[-]
Contingency factor - Modulus of subgrade reaction	f_{kv}	1.6	[-]
Contingency factor - Soil load Qn	f_{Qn2}	1.1	[-]
Contingency factor - Bending moment	f_{M}	1.4	[-]
Contingency factor - Bending radius	f_{R}	n.a.	[-]
Contingency factor - Pressure borehole	$f_{\text{press;bore}}$	1.1	[-]
Effective weight of pipe	g_{eff}	4.069	[N/mm]
Weight of pipeline (incl. filling)	g_{fill}	0.391	[N/mm]
Uplift force	g_{upw}	5.529	[N/mm]
Moment coefficient indirect bottom	k_{b}'	0.083	[-]
Moment coefficient indirect top	k_{t}'	0.061	[-]
Moment coefficient direct bottom	k_{b}	0.138	[-]
Moment coefficient direct top	k_{t}	0.131	[-]

Direct deflection factor	k_y	0.089	[-]
Indirect deflection factor	k_y'	0.048	[-]
Part of pipe filled with water during pull back	P_{water}	10	[%]
Cross sections of the pipe	A	112070.789	[mm^2]
	A_{trek}	112070.789	[mm^2]
	A_{inw}	390584.036	[mm^2]
Minimal wall thickness	$d_{n;min}$	47.4	[mm]
Outer radius of the pipeline	r_e	400	[mm]
Inner radius of the pipeline	r_i	352.6	[mm]
Average radius of the pipeline	r_g	376.3	[mm]
Moment of inertia of the pipe	I_b	7966181061	[mm^4]
Moment of inertia of the wall	I_w	8874.702	[mm^3]
Pipe resisting moment	W_b	19915453	[mm^{4}m]
Wall resisting moment	W_w	374.46	[mm^{3}m]
Unit weight of drilling fluid	$\gamma_{drill\ fluid}$	11	[kN/m^3]
Maximum modulus of subgrade reaction	$k_{v;max}$	51037.814	[kN/m^3]
Maximum neutral vertical soil load	$q_{v;n;r;max}$	184.15	[kN/m^2]
Maximum corrected reduced soil load	q_n	202.565	[kN/m^2]
Maximum neutral horizontal soil load	$q_{h;n;r}$	136.488	[kN/m^2]
Soil reaction - Left curve	$q_{r;left}$	6.057	[kN/m^2]
Soil reaction - Right curve	$q_{r;right}$	4.543	[kN/m^2]
Soil reaction - Left curve (long term)	$q_{r;left}$	2.709	[kN/m^2]
Soil reaction - Right curve (long term)	$q_{r;right}$	2.031	[kN/m^2]
Characteristic stiffness pipeline-soil	λ	0.0010639	[mm^{-1}]
Characteristic stiffness pipeline-soil (long term)	λ_{long}	0.001591	[mm^{-1}]

The total pulling force is the contribution of five components. Results are given in the table below.

Table 3.34: *Analytical results for the calculation of the five components of the pulling force for the six characteristic points*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	100.79	0	0	0	0	100.79
2	153.91	78.33	144.61	0	0	0	222.93
3	290.04	58.45	0	127.91	5.72	15.25	351.94
4	393.19	43.4	45.17	0	0	0	433.79
5	602.62	12.83	0	196.78	4.29	31.55	635.84
6	690.49	0	82.55	0	0	0	705.56

3.3.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the Report.

Table 3.35: *Results of benchmark 3-03, Buoyancy control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	553	553	0.00
Weight of pipeline (incl. filling)	[kg/m]	146	146	0.00
Effective weight of pipe	[kg/m]	407	407	0.00

Table 3.36: *Results of benchmark 3-03, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	100.79	0	100.79	0.00	0.00
T2	153.91	222.93	153.91	222.93	0.00	0.00
T3	290.04	351.94	290.05	351.94	0.00	0.00
T4	393.19	433.79	393.19	433.79	0.00	0.00
T5	602.62	635.84	602.63	635.84	0.00	0.00
T6	690.49	705.56	690.49	705.56	0.00	0.00
Max. rep. pulling force	-	829	-	829	-	0.00

Table 3.37: *Results of benchmark 3-03, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.56	0.56	0.00
σ_t	[N/mm^2]	1.26	1.26	0.00
$\sigma_{a;max}$	[N/mm^2]	1.62	1.62	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.38: *Results of benchmark 3-03, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.93	0.93	0.00
σ_t	[N/mm^2]	8.81	8.81	0.00
$\sigma_{a;max}$	[N/mm^2]	9.42	9.42	0.00
λ	[mm^{-1}]	0.001064	0.001064	0.00
q_r	[N/mm^2]	0.00606	0.00606	0.00
σ_{qr}	[N/mm^2]	0.4	0.4	0.00
$\sigma_{t;max}$	[N/mm^2]	0.4	0.4	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.39: *Results of benchmark 3-03, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	4.78	4.78	0.00
σ_{px}	[N/mm^2]	2.39	2.39	0.00
σ_{ptest}	[N/mm^2]	6.65	6.65	0.00
σ_{pm}	[N/mm^2]	4.14	4.14	0.00

Table 3.40: *Results of benchmark 3-03, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.19	0.19	0.00
$\sigma_{a;max}$	[N/mm^2]	0.12	0.12	0.00
σ_{qr}	[N/mm^2]	0.18	0.18	0.00
σ_{qr}	[N/mm^2]	22.47	22.47	0.00
$\sigma_{t;max}$	[N/mm^2]	14.72	14.72	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.41: *Results of benchmark 3-03, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.19	0.19	0.00
σ_{py}	[N/mm^2]	4.78	4.78	0.00
σ_{px}	[N/mm^2]	2.39	2.39	0.00
σ_{ptest}	[N/mm^2]	6.65	6.65	0.00
σ_{ptemp}	[N/mm^2]	0.36	0.36	0.00
$\sigma_{a;max}$	[N/mm^2]	2.51	2.51	0.00
σ_{qr}	[N/mm^2]	0.18	0.18	0.00
σ_{qr}	[N/mm^2]	22.47	22.47	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.42: *Results of benchmark 3-03, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	8	8	0.00
σ_{py}	[N/mm^2]	6.3	6.3	0.00
σ_{pm}	[N/mm^2]	n.a.	n.a.	
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (short)	[N/mm^2]	8	8	8
$\sigma_{a/t}$ (long)	[N/mm^2]	6.3	6.3	6.3

Table 3.43: *Results of benchmark 3-03, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	121.4	121.4	0.00
Max. allowable	[mm]	64	64	0.00
Max. allow. (piggability)	[mm]	40	40	0.00

Table 3.44: *Results of benchmark 3-03, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	396.55	396.55	0.00
Max. allow. external pressure (long)	[kPa]	39.66	39.66	0.00
Int. pressure due to 100% filling (short)	[kPa]	0	0	0.00
Int. pressure due to 100% filling (long)	[kPa]	0	0	0.00

Use D-GEO PIPELINE input file bm3-3.dri to run this benchmark.

3.4 HDD with 2D geometry – Steel pipe in two incompressible drained layers

3.4.1 Description

The same input values as benchmark 3-1 (section 3.1) are used, only the position of the boundaries between compressible/incompressible layers and drained/undrained layers is different: the boundary coincides with the surface level.Calculations of the pulling forces and the minimum drilling fluid pressure are independent of the soil material. Therefore, in this benchmark, only the calculation of the maximum drilling fluid pressure and the reduced vertical stress are checked.

3.4.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Soil mechanical data

The soil mechanical data's are determined using the formulas given in chapter "Calculation of soil mechanical data" in the Background section of the User Manual of D-GEO PIPELINE. Intermediate results are given in the tables below.

Table 3.45: *Analytical results – General data's*

Vert.	L	Z	h_p	H_L	h_h	σ_V'	$\sigma_{v;H}$'
[-]	[m]	[m]	[m]	[m]	[m]	[kN/m^2]	[kN/m^2]
1	20	-2.309	1.859	1.898	2.309	32.322	26.574
2	50	-9.235	8.785	8.824	9.235	79.408	76.945
3	100	-20.778	20.328	20.368	20.778	171.781	167.676
4	200	-42.442	41.992	42.037	42.442	388.418	384.367
5	350	-50	49.55	49.6	50	464	460
6	500	-43.481	43.031	43.077	43.481	398.806	394.773
7	650	-10.718	10.268	10.304	10.718	88.308	85.823
8	680	-2.679	2.229	2.265	2.679	37.513	31.715

Table 3.46: *Analytical results for the calculation of the neutral reduced vertical stress*

Vert.	B_1	F_r	$F_{r;max}$	q_{nr1}	q_{nr2}	$q_{v;n}$	$q_{v;r;n}$
[-]	[m]	[kN/m]	[kN/m]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]
1	0.935	n.a.	n.a.	n.a.	n.a.	27.808	27.808
2	0.935	n.a.	n.a.	n.a.	n.a.	77.474	28.587
3	0.862	n.a.	n.a.	n.a.	n.a.	168.557	26.621
4	0.862	n.a.	n.a.	n.a.	n.a.	385.237	28.21
5	0.862	n.a.	n.a.	n.a.	n.a.	460.858	28.448
6	0.862	n.a.	n.a.	n.a.	n.a.	395.638	28.247
7	0.935	n.a.	n.a.	n.a.	n.a.	86.322	28.299
8	0.935	n.a.	n.a.	n.a.	n.a.	32.813	32.813

Maximum drilling fluid pressures

For the maximum drilling fluid pressures in drained conditions, calculations are performed using the formulas given in paragraph "Maximum required drilling fluid pressure" in the Background section of the User Manual of D-GEO PIPELINE [Deltares]. Intermediate results are given in the table below.

Table 3.47: *Analytical results for the calculation of the maximum drilling fluid pressures*

Vert.	u	0.9 p_{limit}	p_{pilot}	$p_{preream}$	p_{back}	p_{pilot}	$p_{preream}$	p_{back}
plastic zone related to :			deformation bore hole			soil cover		
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]
1	0	85.33	93.1	83.32	75.01	93.1	83.32	75.01
2	62.35	111.81	124.13	123.26	122.1	124.13	123.26	122.1
3	177.78	163.77	181.95	181.77	181.53	181.95	181.77	181.53
4	394.42	285.63	317.36	317.32	317.26	317.36	317.32	317.26
5	470	328.15	364.6	364.57	364.53	364.6	364.57	364.53
6	404.81	291.48	323.86	323.82	323.76	323.86	323.82	323.76
7	77.18	116.82	129.72	129.07	128.19	129.72	129.07	128.19
8	0	88.25	96.77	88.89	81.63	96.77	88.89	81.63

3.4.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.48: *Results of benchmark 3-04, Vertical soil stresses*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	47	28	28	47	28	28	0.00	0.00	0.00
2	234	77	29	234	77	29	0.00	0.00	0.00
3	916	169	27	916	169	27	0.00	0.00	0.00
4	1656	385	28	1656	385	28	0.00	0.00	0.00
5	1887	461	28	1887	461	28	0.00	0.00	0.00
6	1688	396	28	1688	396	28	0.00	0.00	0.00
7	253	86	28	253	86	28	0.00	0.00	0.00
8	60	33	33	60	33	33	0.00	0.00	0.00

Table 3.49: *Results of benchmark 3-04, Maximum allowable drilling fluid pressure (plastic zone related to deformation bore hole)*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	48	48	48	48	48	48	0.00	0.00	0.00
2	152	152	152	152	152	152	0.00	0.00	0.00
3	503	503	503	503	503	503	0.00	0.00	0.00
4	992	992	992	992	992	992	0.00	0.00	0.00
5	1153	1153	1153	1153	1153	1153	0.00	0.00	0.00
6	1014	1014	1014	1015	1015	1015	0.1	0.1	0.1
7	175	175	175	175	175	175	0.00	0.00	0.00
8	53	53	53	53	53	53	0.00	0.00	0.00

Table 3.50: *Results of benchmark 3-04, Maximum allowable drilling fluid pressure (plastic zone related to soil cover)*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	88	74	62	88	74	62	0.00	0.00	0.00
2	221	221	221	221	221	221	0.00	0.00	0.00
3	800	800	800	800	800	800	0.00	0.00	0.00
4	1545	1545	1545	1545	1545	1545	0.00	0.00	0.00
5	1785	1785	1785	1785	1785	1785	0.00	0.00	0.00
6	1579	1579	1579	1579	1579	1579	0.00	0.00	0.00
7	249	249	249	249	249	249	0.00	0.00	0.00
8	96	86	74	96	86	74	0.00	0.00	0.00

Use D-GEO PIPELINE input file bm3-4.dri to run this benchmark.

3.5 HDD with 2D geometry – Steel pipe in a sequence of a compressible undrained layer and a compressible drained layer

3.5.1 Description

The same input data's as benchmark 3-1 (section 3.1) are used, except that the position of the boundary between undrained/drained layers is different: the boundary coincides with the top of the sand layer. Changing the position of the boundary between undrained/drained layers will only effect the maximum drilling fluid pressures calculation.

3.5.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Maximum drilling fluid pressures

For the maximum drilling fluid pressures in drained conditions, calculations are performed using the formulas given in paragraph "Maximum required drilling fluid pressure" in the Background section of the User Manual of D-GEO PIPELINE [Deltares]. Intermediate results are given in the table below.

Table 3.51: *Analytical results for the calculation of the maximum drilling fluid pressures*

Vert.	u	0.9 p_{limit}	p_{pilot}	$p_{preream}$	p_{back}	p_{pilot}	$p_{preream}$	p_{back}
plastic zone related to :			deformation bore hole			soil cover		
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]
1	0	88.6	95.29	80.21	69.47	95.29	80.21	69.47
2	62.35	122.71	136.09	134.22	131.85	136.09	134.22	131.85
3	177.78	180.76	200.46	197.59	194.1	200.46	197.59	194.1
4	394.42	302.62	336.23	336.09	335.9	336.23	336.09	335.9
5	470	345.13	383.47	383.39	383.27	383.47	383.39	383.27
6	404.81	308.46	342.72	342.59	342.41	342.72	342.59	342.41
7	77.18	129.29	143.47	142.02	140.14	143.47	142.02	140.14
8	0	91.95	99.75	87.08	77.24	99.75	87.08	77.24

The intermediate analytical results for the calculation of the maximum drilling fluid pressures in drained conditions are the same as benchmark 3-4 (see section 3.4.2).

3.5.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.52: *Results of benchmark 3-05, Maximum allowable drilling fluid pressure (plastic zone related to deformation bore hole)*

	Benchmark			D-GEO PIPELINE			Relative error		
	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back
	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	89	80	69	89	80	69	0.00	0.00	0.00
2	185	185	185	185	185	185	0.00	0.00	0.00
3	503	503	503	502	502	502	0.2	0.2	0.2
4	992	992	992	992	992	992	0.00	0.00	0.00
5	1153	1153	1153	1153	1153	1153	0.00	0.00	0.00
6	1014	1014	1014	1014	1014	1014	0.00	0.00	0.00
7	206	206	206	206	206	206	0.00	0.00	0.00
8	92	87	77	92	87	77	0.00	0.00	0.00

Table 3.53: *Results of benchmark 3-05, Maximum allowable drilling fluid pressure (plastic zone related to soil cover)*

	Benchmark			D-GEO PIPELINE			Relative error		
nr.	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back	Pilot	Pre-ream	Pull back
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	89	80	69	89	80	69	0.00	0.00	0.00
2	185	185	185	185	185	185	0.00	0.00	0.00
3	800	767	697	799	766	696	0.13	0.13	0.14
4	1545	1545	1545	1545	1545	1545	0.00	0.00	0.00
5	1785	1785	1785	1785	1785	1785	0.00	0.00	0.00
6	1579	1579	1579	1578	1578	1578	0.06	0.06	0.06
7	206	206	206	206	206	206	0.00	0.00	0.00
8	92	87	77	92	87	77	0.00	0.00	0.00

Use D-GEO PIPELINE input file bm3-5.dri to run this benchmark.

3.6 HDD with 2D geometry – Steel pipe in a sequence of an incompressible undrained layer and an incompressible drained layer

3.6.1 Description

The same input data's as benchmark 3-1 (section 3.1) are used, except for the position of the boundary between undrained/drained layers which coincides with the top of the sand layer and for the boundary between compressible/incompressible layers which coincides with the top of the ground line. Changing the position of the boundary between undrained/drained layers will only affect the maximum drilling fluid pressures calculation and changing the position of the boundary between compressible/incompressible layers will only affect the neutral reduced

vertical stress.

3.6.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Soil mechanical data

The soil mechanical data's are determined using the formulas given in chapter "Calculation of soil mechanical data" in the Background section of the User Manual of D-GEO PIPELINE. Intermediate results are given in the tables below. Analytical results for the neutral reduced vertical stress are the same as benchmark 3-4 (section 3.4.2) because the position of the boundary between compressible/incompressible layers is the same.

Maximum drilling fluid pressures

For the maximum drilling fluid pressures in drained conditions, calculations are performed using the formulas given in paragraph "Maximum required drilling fluid pressure" in the Background section of the User Manual of D-GEO PIPELINE [Deltares]. Analytical results for the maximum drilling fluid pressures are the same as benchmark 3-5 (section 3.5.2) because the position of the boundary between undrained/drained layers is the same.

3.6.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.54: *Results of benchmark 3-06, Vertical soil stresses*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
nr.	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	47	28	28	47	28	28	0.00	0.00	0.00
2	234	77	29	234	77	29	0.00	0.00	0.00
3	916	169	27	916	169	27	0.00	0.00	0.00
4	1656	385	28	1656	385	28	0.00	0.00	0.00
5	1887	461	28	1887	461	28	0.00	0.00	0.00
6	1688	396	28	1688	396	28	0.00	0.00	0.00
7	253	86	28	253	86	28	0.00	0.00	0.00
8	60	33	33	60	33	33	0.00	0.00	0.00

Use D-GEO PIPELINE input file bm3-6.dri to run this benchmark.

3.7 HDD with 3D geometry – Steel pipe in 4 layers – Compressible border above drainage border

3.7.1 Description

The pipe is constructed in four compressible undrained layers with the characteristics given in Table 3.57. The boundaries between compressible/uncompressible layers and drained/undrained layers are respectively situated at the bottom of the second and third layers. The ground level is not plane as shown in Figure 3.3 and the phreatic line is at depth Z_{phreatic} = -5 m. The hydraulic head at the surface level is 1 m and 10 m at the bottom (i.e. Z = -46 m). The steel pipe properties are given in Table 3.56. Calculations are performed for 8 verticals with

L coordinates of 60, 100, 150, 170, 1000, 1650, 1775 and 1800 m. The configuration of the pipeline is given by:

X_{left}	50 m	X-coordinate of the left entry point
Y_{left}	-5 m	Y-coordinate of the left entry point
Z_{left}	-2 m	Z-coordinate of the left entry point
X_{right}	1800 m	X-coordinate of the right exit point
Y_{right}	104.21 m	Y-coordinate of the right exit point
Z_{right}	10 m	Z-coordinate of the right exit point
φ_{left}	13°	Left angle of the pipe
φ_{right}	15°	Right angle of the pipe
Z_{bottom}	-45 m	Lowest level of the pipe
R_{left}	1300 m	Bending radius of the pipe at the left side
R_{right}	1050 m	Bending radius of the pipe at the right side
R_{rol}	800 m	Bending radius in pipe string (on rollers)

with two horizontal bendings:

		bending 1	bending 2
X-coordinate of the first point X_1	[m]	450	800
Z-coordinate of the first point Z_1	[m]	10	106.880
X-coordinate of the second point X_2	[m]	687.664	1313.615
Z-coordinate of the second point Z_2	[m]	61.157	171.288
Bending radius	[m]	700.004	1000.008
Direction		Right	Left

Table 3.55: *Soil material properties (benchmark 3-07)*

			Mat 1	Mat 2	Mat 3	Mat 4
Unit weight above phreatic level	γ_{unsat}	[kN/m^3]	18	17	14	11
Unit weight below phreatic level	γ_{sat}	[kN/m^3]	20	19	16	13
Cohesion	c	[kN/m^2]	0.2	1.5	5	20
Angle of internal friction	φ	[°]	35	30	0	15
Undrained cohesion top	$C_{\text{u;top}}$	[kN/m^2]	1	3	30	50
Undrained cohesion bottom	$C_{\text{u;bottom}}$	[kN/m^2]	2	5	25	40
Young modulus top	$E_{\text{u;top}}$	[kN/m^2]	20000	30000	1500	1000
Young modulus bottom	$E_{\text{u;bottom}}$	[kN/m^2]	25000	40000	2000	500
Poisson ratio	ν	[-]	0.5	0.45	0.25	0.35

Table 3.56: *Pipe material data (benchmark 3-07)*

Material			Steel
Negative wall thickness tolerance	δt	[%]	25
Yield strength	R_{e}	[N/mm^2]	200
Partial material factor	γ_{m}	[-]	1.3
Partial material factor for test pressure	$\gamma_{\text{m;test}}$	[-]	1.15
Young's modulus	E_{b}	[N/mm^2]	180500
Outer diameter	D_0	[m]	1.5
Nominal wall thickness	d_{n}	[mm]	35
Unit weight	γ_{b}	[kN/m^3]	65
Design pressure	p_{d}	[kN/m^2]	500
Test pressure	p_{t}	[kN/m^2]	900
Temperature variation	Δt	[°]	10

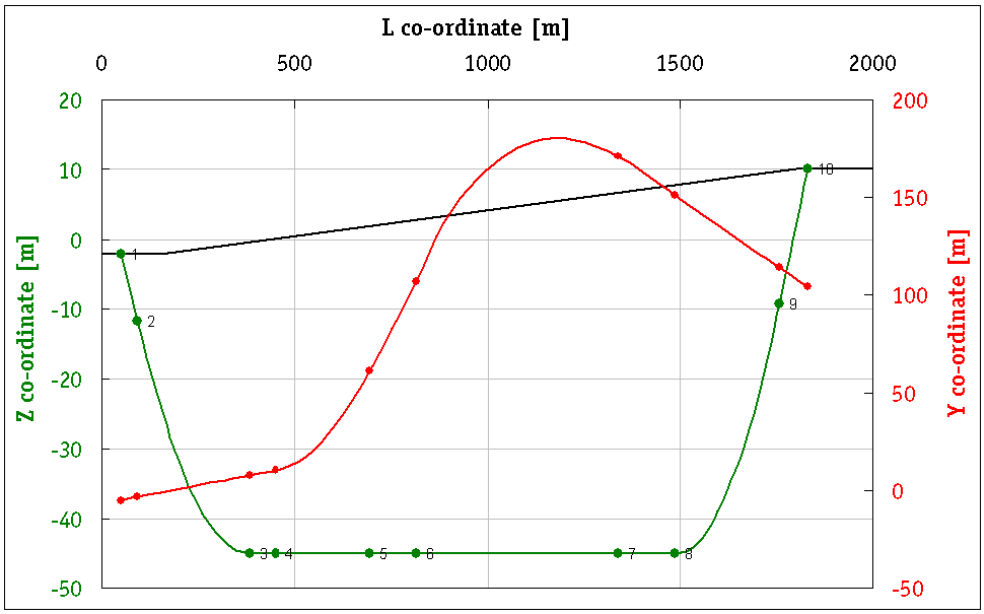

Figure 3.3: *3D view of the pipeline configuration (benchmark 3-7)*

3.7.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Soil mechanical data

The soil mechanical data's are determined using the formulas given in chapter "Calculation of soil mechanical data" in the Background section of the User Manual of D-GEO PIPELINE. The maximal axial friction between the pipe and the drilling fluid is constant along the pipeline and equal to f_2 = 50 N/m^2. The displacement necessary to develop the maximal axial friction along the pipeline is estimated between 6 and 9 mm (= 7.5 mm).

Strength calculation

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter "Strength pipeline calculation" in the Background section of the User Manual of D-GEO PIPELINE. The length of the pipe in the borehole at the 10 characteristic points (see Figure 3.3) is:

Table 3.57: *Position of the characteristic points (benchmark 3-07a)*

Point	L-coord.	X-coord.	Z-coord.	Traject length
	[m]	[m]	[m]	[m]
1	50	50	-2	0
2	91.93	91.9	-11.68	43.036
3	384.37	384.13	-45	337.997
4	450.28	450	-45	403.908
5	694.63	687.66	-45	648.255
6	815.91	800	-45	769.539
7	1339.51	1313.62	-45	1293.138
8	1487	1459.72	-45	1440.628
9	1758.76	1728.93	-9.22	1715.518
10	1830.5	1800	10	1789.786

Hereafter are some intermediate results used for the pulling force and the strength calculations:

Factor of friction pipe-roller	f_1	0.2	[-]
Friction pipe-mud	f_2	0.00035	[N/mm^2]
Factor of friction pipe-soil	f_3	0.3	[-]
Load factor - Design pressure	f_{pd}	1.1	[-]
Load factor - Design pressure (combination)	$f_{pd;comb}$	1.3	[-]
Load factor - Test pressure	f_{pt}	0.9	[-]
Load factor - Installation	$f_{install}$	1.2	[-]
Load factor - Soil load Qn	f_{Qn1}	1.3	[-]
Load factor - Temperature	f_{temp}	1.2	[-]
Contingency factor - E-modulus	f_E	1.4	[-]
Contingency factor - Pulling force	f_{pull}	1.1	[-]
Contingency factor - Modulus of subgrade reaction	f_{kv}	1.1	[-]
Contingency factor - Soil load Qn	f_{Qn2}	1.2	[-]
Contingency factor - Bending moment	f_M	1.15	[-]
Contingency factor - Bending radius	f_R	1.3	[-]
Contingency factor - Pressure borehole	$f_{press;bore}$	1.15	[-]
Effective weight of pipe	g_{eff}	10.093	[N/mm]
Weight of pipeline (incl. filling)	g_{fill}	2.409	[N/mm]
Uplift force	g_{upw}	22.973	[N/mm]
Moment coefficient indirect bottom	k_b'	0.073	[-]
Moment coefficient indirect top	k_t'	0.056	[-]
Moment coefficient direct bottom	k_b	0.139	[-]
Moment coefficient direct top	k_t	0.139	[-]
Direct deflection factor	k_y	0.091	[-]
Indirect deflection factor	k_y'	0.043	[-]
Part of pipe filled with water during pull back	P_{water}	15	[%]
Cross sections of the pipe	A	121535.457	[mm^2]
	A_{trek}	161085.163	[mm^2]
	A_{inw}	1606060.704	[mm^2]
Minimal wall thickness	$d_{n;min}$	26.25	[mm]
Outer radius of the pipeline	r_e	750	[mm]
Inner radius of the pipeline	r_i	715	[mm]
Average radius of the pipeline	r_g	732.5	[mm]
Moment of inertia of the pipe	I_b	43240291745	[mm^4]
Moment of inertia of the wall	I_w	3572.917	[mm^3]
Pipe resisting moment	W_b	57653722	[mm^{4}m]
Wall resisting moment	W_w	204.167	[mm^{3}m]
Unit weight of drilling fluid	$\gamma_{drill\ fluid}$	13	[kN/m^3]
Maximum modulus of subgrade reaction	$k_{v;max}$	20467.554	[kN/m^3]
Maximum neutral vertical soil load	$q_{v;n;r;max}$	154.787	[kN/m^2]
Maximum traffic load	$q_{T;max}$	5	[kN/m^2]
Max. red. neutral vertical soil load (incl. traffic load)	$q_{v;n;r;maxT}$	154.787	[kN/m^2]
Max. corrected red. soil load (without traffic load)	q_n	241.467	[kN/m^2]
Max. corrected red. soil load (incl. traffic load)	q_{nT}	241.467	[kN/m^2]
Maximum neutral horizontal soil load	$q_{h;n;r}$	101.846	[kN/m^2]
Soil reaction - Left curve	$q_{r;left}$	52.606	[kN/m^2]
Soil reaction - Right curve	$q_{r;right}$	65.131	[kN/m^2]
Soil reaction - Left curve (long term)	$q_{r;left}$	n.a.	[kN/m^2]
Soil reaction - Right curve (long term)	$q_{r;right}$	n.a.	[kN/m^2]
Characteristic stiffness pipeline-soil	λ	0.0001771	[mm^{-1}]

Characteristic stiffness pipeline-soil (long term)	λ_{long}	n.a.	[mm^{-1}]

The total pulling force is the contribution of five components. Two cases are checked:

- ◇ Case A (bm3-7a): pulling direction from left to right (see results in Table 3.59);
- ◇ Case B (bm3-7b): pulling direction from right to left (see results in Table 3.60).

Table 3.59: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points for case a*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	4610.36	0	0	0	0	4610.36
2	43.04	4499.5	201.29	0	0	0	4700.79
3	338	3739.7	0	1379.62	839.93	418.44	6578.99
4	403.91	3569.92	308.29	0	0	0	6717.5
5	648.25	2940.5	0	2702.75	889.15	0	9679.98
6	769.54	2628.08	567.29	0	0	0	9934.85
7	1293.14	1279.33	0	3540.94	1797.78	0	13924.82
8	1440.63	899.4	689.86	0	0	0	14234.75
9	1715.52	191.31	0	1285.74	1039.92	823.38	16675.7
10	1789.79	0	347.38	0	0	0	16831.77

Table 3.60: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points for case b*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
10	0	4610.36	0	0	0	0	4610.36
9	74.27	4419.05	347.38	0	0	0	4766.42
8	349.16	3710.95	0	1285.74	1039.92	499.97	6883.96
7	496.65	3331.03	689.86	0	0	0	7193.89
6	1020.25	1982.28	0	3540.94	1372.13	0	10758.22
5	1141.53	1669.86	567.29	0	0	0	11013.08
4	1385.88	1040.44	0	2702.75	1336.7	0	14423.12
3	1451.79	870.66	308.29	0	0	0	14561.63
2	1746.75	110.86	0	1379.62	839.93	724.1	16745.49
1	1789.79	0	201.29	0	0	0	16835.92

3.7.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.61: *Results of benchmark 3-07a, Vertical soil stresses*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	24	19	19	24	19	19	0.00	0.00	0.00
2	74	24	24	74	24	24	0.00	0.00	0.00
3	582	114	52	582	114	53	0.00	0.00	1.89
4	913	156	60	913	156	59	0.00	0.00	1.69
5	2006	442	52	2006	442	52	0.00	0.00	0.00
6	1610	346	107	1610	346	107	0.00	0.00	0.00
7	284	155	155	284	155	155	0.00	0.00	0.00
8	203	83	83	204	83	83	0.49	0.00	0.00

Table 3.62: *Results of benchmark 3-07a, Neutral horizontal soil stress and bearing capacities*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	12	442	98	12	442	99	0.00	0.00	1.01
2	16	196	115	16	196	115	0.00	0.00	0.00
3	34	3332	794	35	3332	794	2.86	0.00	0.00
4	39	4449	1020	39	4449	1020	0.00	0.00	0.00
5	34	21154	2006	34	21154	2006	0.00	0.00	0.00
6	71	16672	1610	71	16672	1610	0.00	0.00	0.00
7	102	1233	284	102	1233	284	0.00	0.00	0.00
8	55	831	211	55	831	211	0.00	0.00	0.00

Table 3.63: *Results of benchmark 3-07a, Vertical and horizontal moduli of subgrade reaction*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h
[-]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[%]	[%]	[%]
1	253	190	133	253	190	133	0.00	0.00	0.00
2	188	2365	1655	188	2365	1655	0.00	0.00	0.00
3	3871	12208	8546	3871	12208	8546	0.00	0.00	0.00
4	9140	13024	9117	9140	13024	9117	0.00	0.00	0.00
5	8287	9074	6352	8287	9074	6352	0.00	0.00	0.00
6	10516	7949	5564	10516	7949	5564	0.00	0.00	0.00
7	184	309	216	184	309	216	0.00	0.00	0.00
8	233	166	116	233	166	116	0.00	0.00	0.00

Table 3.64: *Results of benchmark 3-07a, Maximal axial friction and displacements*

	Benchmark			D-GEO PIPELINE			Relative error		
Vert.	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}
[-]	[kN/m^2]	[mm]	[mm]	[kN/m^2]	[mm]	[mm]	[%]	[%]	[%]
1	0.35	5	8	0	5	8	0.00	0.00	0.00
2	0.35	10	8	0	10	8	0.00	0.00	0.00
3	0.35	20	8	0	20	8	0.00	0.00	0.00
4	0.35	40	8	0	40	8	0.00	0.00	0.00
5	0.35	80	8	0	80	8	0.00	0.00	0.00
6	0.35	60	8	0	60	8	0.00	0.00	0.00
7	0.35	50	8	0	50	8	0.00	0.00	0.00
8	0.35	35	8	0	35	8	0.00	0.00	0.00

Table 3.65: *Results of benchmark 3-07a, Pulling forces in the pipeline*

	Benchmark		D-GEO PIPELINE		Relative error	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	4610	0	4610	0.00	0.00
T2	43	4701	43	4701	0.00	0.00
T3	338	6579	338	6579	0.00	0.00
T4	1441	14235	1441	14235	0.00	0.00
T5	1716	16676	1716	16676	0.00	0.00
T6	1790	16832	1790	16832	0.00	0.00
Max. rep. pulling force	-	0	-	0	-	0.00

Table 3.66: *Results of benchmark 3-07b, Pulling forces in the pipeline*

	Benchmark		D-GEO PIPELINE		Relative error	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	4610	0	4610	0.00	0.00
T2	74	4766	74	4766	0.00	0.00
T3	349	6884	349	6884	0.00	0.00
T4	1452	14562	1452	14562	0.00	0.00
T5	1747	16745	1747	16745	0.00	0.00
T6	1790	16836	1790	16836	0.00	0.00
Max. rep. pulling force	-	0	-	0	-	0.00

Use D-GEO PIPELINE input files bm3-7a.dri and bm3-7b.dri to run this benchmark.

3.8 Special strength analysis

3.8.1 Description

The same input values as for benchmark 3-7a (section 3.7) are used. Calculations are performed using the Special Stress Analysis calculation which means that the maximum modulus of subgrade reaction and the maximum reduced soil load are input values instead of calculated values: $k_{V;max}$ = 45000 kN/m^3, $q_{n;max}$ = 0.14 N/mm^2 and R = 700 m.

3.8.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Strength calculation

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter “Strength pipeline calculation” in the Background section of the User Manual of D-GEO PIPELINE. The total pulling force is the contribution of five components. Results are given in Table 3.67.

Table 3.67: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-08)*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
2	43.04	4499.5	201.29	0	0	0	4700.79
3	338	3739.7	0	1379.62	1022.78	430.86	6774.25
4	403.91	3569.92	308.29	0	0	0	6912.76
5	648.25	2940.5	0	3042.32	944.88	0	10270.54
6	769.54	2628.08	567.29	0	0	0	10525.4
7	1293.14	1279.33	0	3778.64	1926.4	0	14881.69
8	1440.63	899.4	689.86	0	0	0	15191.62
9	1715.52	191.31	0	1285.74	1266.3	856.4	17891.97
10	1789.79	0	347.38	0	0	0	18048.04
	0	0	0	0	0	0	0

3.8.3 D-GEO PIPELINE results

A *Special Stress Analysis* calculation must be performed by selecting *Special Stress Analysis* for the *Start* menu. D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.68: *Results of benchmark 3-08, Buoyancy Control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	2297	2297	0.00
Weight of pipeline (incl. filling)	[kg/m]	1288	1288	0.00
Effective weight of pipe	[kg/m]	1009	1009	0.00

Table 3.69: *Results of benchmark 3-08, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	4610	0	4610	0.00	0.00
T2	43	4701	43	4701	0.00	0.00
T3	338	6774	338	6774	0.00	0.00
T4	1441	15192	1441	15192	0.00	0.00
T5	1716	17892	1716	17892	0.00	0.00
T6	1790	18048	1790	18048	0.00	0.00
Max. rep. pulling force	-	0	-	0	-	0.00

Table 3.70: *Results of benchmark 3-08, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	304	304	0.00
σ_t	[N/mm^2]	50	50	0.00
$\sigma_{a;max}$	[N/mm^2]	354	354	0.00
$\sigma_{V;max}$	[N/mm^2]	354	354	0.00

Table 3.71: *Results of benchmark 3-08, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	347	347	0.00
σ_t	[N/mm^2]	196	196	0.00
$\sigma_{a;max}$	[N/mm^2]	543	543	0.00
λ	[mm^{-1}]	0.000216	0.000216	0.00
q_r	[N/mm^2]	0.1449	0.1449	0.00
σ_{qr}	[N/mm^2]	57	57	0.00
$\sigma_{t;max}$	[N/mm^2]	57	57	0.00
$\sigma_{V;max}$	[N/mm^2]	574	574	0.00

Table 3.72: *Results of benchmark 3-08, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	15	15	0.00
σ_{px}	[N/mm^2]	8	8	0.00
σ_{ptest}	[N/mm^2]	23	23	0.00
σ_{pm}	[N/mm^2]	13	13	0.00

Table 3.73: *Results of benchmark 3-08, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	347	347	0.00
$\sigma_{a;max}$	[N/mm^2]	347	347	0.00
σ_{qr}	[N/mm^2]	57	57	0.00
σ_{qr}	[N/mm^2]	164	164	0.00
$\sigma_{t;max}$	[N/mm^2]	222	222	0.00
$\sigma_{V;max}$	[N/mm^2]	496	496	0.00

Table 3.74: *Results of benchmark 3-08, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	347	347	0.00
σ_{py}	[N/mm^2]	18	18	0.00
σ_{px}	[N/mm^2]	9	9	0.00
σ_{ptest}	[N/mm^2]	23	23	0.00
σ_{ptemp}	[N/mm^2]	15	15	0.00
$\sigma_{a;max}$	[N/mm^2]	356	356	0.00
σ_{qr}	[N/mm^2]	57	57	0.00
σ_{qr}	[N/mm^2]	164	164	0.00
$\sigma_{V;max}$	[N/mm^2]	484	484	0.00

Table 3.75: *Results of benchmark 3-08, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	173.91	173.91	0.00
σ_{py}	[N/mm^2]	153.85	153.85	0.00
σ_{pm}	[N/mm^2]	169.23	169.23	0.00
$\sigma_{V;max}$	[N/mm^2]	261.54	261.54	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.76: *Results of benchmark 3-08, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	16.1	16.1	0.00
Max. allowable	[mm]	255	255	0.00
Max. allow. (piggability)	[mm]	120	120	0.00

Table 3.77: *Results of benchmark 3-08, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Use D-GEO PIPELINE input file bm3-8.dri to run this benchmark.

3.9 HDD with 3D geometry – Bundled pipeline (3 steel pipes and 2 PE pipes)

3.9.1 Description

The same input as for benchmark 3-7a (section 3.7) is used except that five pipes are used instead of one. Their characteristics are given in Table 3.78.

Table 3.78: *Pipe material data (benchmark 3-09)*

		PE80	**FE385**	**PE100**	**FE360**	**Steel 1**
Material		Synthetic	Steel	Synthetic	Steel	Steel
δ_t	[%]		10		15	25
E_b	[N/mm^2]	1000	205800	1200	205800	180500
$E_{pipe;long}$	[N/mm^2]	200		300		
R_{eb}	[N/mm^2]	8	385	10	360	200
$R_{eb;long}$	[N/mm^2]	6.3		8		
γ_m	[-]		1.2		1.1	1.3
$\gamma_{m;test}$	[-]		1.1		1.05	1.15
α	[-]	0.65		0.5		
D_0	[mm]	50	219.1	355	457	1000
d_n	[mm]	3.7	22.2	26.1	9.52	35
γ_b	[kN/m^3]	9.54	85	13	78.5	65
p_d	[Bar]	3	3	5	4	5
p_t	[Bar]	6	6	5.5	6.5	9
ΔT	[°C]	5	4	6	8	10

3.9.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Strength calculation for bundled pipelines

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter “Strength pipeline calculation” in the Background section of the User Manual of D-GEO PIPELINE. The pulling force is calculated for an equivalent pipeline with the parameters of the bundle:

$$EI_{eq} = \sum_{i=1}^{n} EI_i \tag{3.1}$$

$$G_{tot} = \sum_{i=1}^{n} \left(\frac{\pi}{4} D_{0;i}^2 - \frac{\pi}{4} \left(D_{0;i} - 2 \times d_{n;i} \right)^2 \right) \times \gamma_i \tag{3.2}$$

$$D_{eq} = f \times \sum_{i=1}^{n} D_{0;i} \tag{3.3}$$

$$\frac{G_{tot}}{\gamma_{eq}} = \frac{\pi}{4} \left(D_{eq}^2 - \left(D_{eq} - 2 \times d_{n;eq} \right)^2 \right) \tag{3.4}$$

$$d_{\text{n;eq}} = \frac{D_{\text{eq}} - \sqrt{D_{\text{eq}}^2 - \sum_{i=1}^{n} D_{\text{0;i}}^2 - \left(D_{\text{0;i}} - 2 \times d_{\text{n;i}}\right)^2}}{2} \tag{3.5}$$

The properties of the equivalent pipe are:

D_{eq}	[mm]	1284.11
$d_{\text{n;eq}}$	[mm]	41.16
γ_{eq}	[kN/m^3]	58.92
I_{eq}	[m^4]	0.031073
E_{eq}	[N/mm^2]	74520.87
$k_{\text{V;max;eq}}$	[kN/m^3]	24550.63

The calculated pulling force is acting on all the pipelines in the bundle. The magnitude of the pulling force of a single pipeline can be determined as follows:

$$T_{\text{i}} = \frac{A_{\text{i}}}{\sum_{i=1}^{n} A_{\text{i}}} \times T_{\text{total}} \quad \text{where} \quad A_{\text{i}} = \frac{\pi}{4} D_{\text{0;i}}^2 - \frac{\pi}{4} \left(D_{\text{0;i}} - 2 \times d_{\text{n;i}}\right)^2 \tag{3.6}$$

The total pulling force is the contribution of five components. Results are given in the 6 tables below, for the equivalent pipeline and for each single pipeline.

Table 3.79: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-09)*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	3887.97	0	0	0	0	3887.97
2	43.04	3794.48	103.16	0	0	0	3897.64
3	338	3153.74	0	707.01	339.9	292.32	4596.13
4	403.91	3010.56	157.99	0	0	0	4610.93
5	648.25	2479.76	0	1216.92	549.03	0	5846.09
6	769.54	2216.29	290.72	0	0	0	5873.34
7	1293.14	1078.88	0	1696.91	989.82	0	7422.66
8	1440.63	758.48	353.53	0	0	0	7455.79
9	1715.52	161.33	0	658.9	420.82	417.14	8355.52
10	1789.79	0	178.02	0	0	0	8372.2

Table 3.80: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-09)*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	2.6	0	0	0	0	2.6
2	43.04	2.54	2.6	0	0	0	5.14
3	338	2.11	0	17.83	0	1.53	24.08
4	403.91	2.02	3.98	0	0	0	27.97
5	648.25	1.66	0	14.77	3.66	0	46.05
6	769.54	1.48	7.33	0	0	0	53.21
7	1293.14	0.72	0	31.65	10.66	0	94.76
8	1440.63	0.51	8.92	0	0	0	103.46
9	1715.52	0.11	0	16.62	0	8.25	127.93
10	1789.79	0	4.49	0	0	0	132.31

Table 3.81: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-09)*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	430.7	0	0	0	0	430.7
2	43.04	420.34	19.57	0	0	0	439.92
3	338	349.36	0	134.16	7.01	34.65	544.75
4	403.91	333.5	29.98	0	0	0	558.87
5	648.25	274.7	0	124.15	62.31	0	686.52
6	769.54	245.52	55.16	0	0	0	712.5
7	1293.14	119.52	0	247.26	120.77	0	954.53
8	1440.63	84.02	67.08	0	0	0	986.12
9	1715.52	17.87	0	125.03	8.67	66.45	1120.12
10	1789.79	0	33.78	0	0	0	1136.03

Table 3.82: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-09)*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	164.16	0	0	0	0	164.16
2	43.04	160.21	27.49	0	0	0	187.7
3	338	133.16	0	188.42	0.46	23.74	373.27
4	403.91	127.11	42.1	0	0	0	409.33
5	648.25	104.7	0	156.95	49.7	0	593.56
6	769.54	93.58	77.47	0	0	0	659.91
7	1293.14	45.55	0	335.07	124.81	0	1071.77
8	1440.63	32.03	94.21	0	0	0	1152.45
9	1715.52	6.81	0	175.59	0.57	88.3	1391.71
10	1789.79	0	47.44	0	0	0	1432.33

Table 3.83: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-09)*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	456.95	0	0	0	0	456.95
2	43.04	445.96	32.68	0	0	0	478.64
3	338	370.66	0	223.95	23.85	44.23	695.36
4	403.91	353.83	50.04	0	0	0	728.57
5	648.25	291.44	0	229.82	86.94	0	982.95
6	769.54	260.48	92.09	0	0	0	1044.07
7	1293.14	126.8	0	428.55	187.44	0	1526.37
8	1440.63	89.14	111.98	0	0	0	1600.7
9	1715.52	18.96	0	208.71	29.53	111.14	1879.89
10	1789.79	0	56.39	0	0	0	1917.32

Table 3.84: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-09)*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	2833.56	0	0	0	0	2833.56
2	43.04	2765.42	76.94	0	0	0	2842.36
3	338	2298.45	0	527.34	324.47	219.2	3446.4
4	403.91	2194.1	117.84	0	0	0	3459.89
5	648.25	1807.25	0	1039.44	425.87	0	4538.35
6	769.54	1615.24	216.84	0	0	0	4563.17
7	1293.14	786.29	0	1357.92	782.44	0	5874.58
8	1440.63	552.78	263.69	0	0	0	5904.76
9	1715.52	117.58	0	491.46	401.73	323.45	6686.2
10	1789.79	0	132.78	0	0	0	6701.4

In this benchmark, the stiffness of the steel and PE materials is significantly different. Therefore, a different approach is applied. In addition to the previous equation, the total pulling force is divided over the stiff steel pipelines. Table 3.85 gives the maximal calculated pulling forces for each pipeline in both cases: single and bundled calculation.

Table 3.85: *Maximal pulling forces without partial factors (bm3-09)*

	A_i	$T_{max;i}$ (Single)	$T_{max;i}$ (Bundled steel pipes)
	[mm^2]	[kN]	[kN]
PE80	538.19	132.31	132.56
FE385	13732.47	1346.74	827.11[1)]
PE100	26968.34	1432.33	1432.33
FE360	13383.21	892.91	806.11[2)]
Steel 1	106107.29	6369.34	6391.12[3)]
Bundled (all)	160729.50	8024.37	
Bundled (only steel)	133222.97		

[1)] 827.11 = 8024.37 $\times$ 13732.47 / 133222.97

[2)] 806.11 = 8024.37 $\times$ 13383.21 / 133222.97

[3)] 6391.12 = 8024.37 $\times$ 106107.29 / 133222.97

3.9.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.86: *Results of benchmark 3-09, Buoyancy control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	1414	1415	0.07
Weight of pipeline (incl. filling)	[kg/m]	1086	1086	0.00
Effective weight of pipe	[kg/m]	328	328	0.00

Table 3.87: *Results of benchmark 3-09, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	3887.97	0	3887.97	0.00	0.00
T2	43.04	3897.64	43.04	3897.64	0.00	0.00
T3	338	4596.13	338	4596.13	0.00	0.00
T4	1440.63	7455.79	1440.63	7455.8	0.00	0.00
T5	1715.52	8355.52	1715.52	8355.52	0.00	0.00
T6	1789.79	8372.2	1789.79	8372.21	0.00	0.00
Max. rep. pulling force	-	4	-	4	-	0.00

Table 3.88: *Results of benchmark 3-09 for pipe nr. 1, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.04	0.04	0.00
σ_t	[N/mm^2]	5.32	5.32	0.00
$\sigma_{a;max}$	[N/mm^2]	5.34	5.34	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.89: *Results of benchmark 3-09 for pipe nr. 1, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.04	0.04	0.00
σ_t	[N/mm^2]	270.44	270.44	0.00
$\sigma_{a;max}$	[N/mm^2]	270.46	270.46	0.00
λ	[mm^{-1}]	0.016823	0.016823	0.00
q_r	[N/mm^2]	0.00038	0.00038	0.00
σ_{qr}	[N/mm^2]	0.01	0.01	0.00
$\sigma_{t;max}$	[N/mm^2]	0.01	0.01	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.90: *Results of benchmark 3-09 for pipe nr. 1, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	1.89	1.89	0.00
σ_{px}	[N/mm^2]	0.94	0.94	0.00
σ_{ptest}	[N/mm^2]	3.78	3.78	0.00
σ_{pm}	[N/mm^2]	1.64	1.64	0.00

Table 3.91: *Results of benchmark 3-09 for pipe nr. 1, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	0.01	0.01	0.00
$\sigma_{a;max}$	[N/mm^2]	0.01	0.01	0.00
σ_{qr}	[N/mm^2]	0.01	0.01	0.00
σ_{qn}	[N/mm^2]	5.96	5.96	0.00
$\sigma_{t;max}$	[N/mm^2]	3.88	3.88	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.92: *Results of benchmark 3-09 for pipe nr. 1, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	0.01	0.01	0.00
σ_{py}	[N/mm^2]	1.89	1.89	0.00
σ_{px}	[N/mm^2]	0.94	0.94	0.00
σ_{ptest}	[N/mm^2]	3.78	3.78	0.00
σ_{ptemp}	[N/mm^2]	0.18	0.18	0.00
$\sigma_{a;max}$	[N/mm^2]	0.95	0.95	0.00
σ_{qr}	[N/mm^2]	0.01	0.01	0.00
σ_{qn}	[N/mm^2]	5.96	5.96	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.93: *Results of benchmark 3-09 for pipe nr. 1, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	6.4	6.4	0.00
σ_{py}	[N/mm^2]	5.04	5.04	0.00
σ_{pm}	[N/mm^2]	n.a.	n.a.	
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (short)	[N/mm^2]	6.4	6.4	0.00
$\sigma_{a/t}$ (long)	[N/mm^2]	5.04	5.04	0.00

Table 3.94: *Results of benchmark 3-09 for pipe nr. 1, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	2.4	2.4	0.00
Max. allowable	[mm]	4	4	0.00
Max. allow. (piggability)	[mm]	2.8	2.8	0.00

Table 3.95: *Results of benchmark 3-09 for pipe nr. 1, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	607.55	607.55	0.00
Max. allow. external pressure (long)	[kPa]	60.76	60.76	0.00
Int. pressure due to 100% filling (short)	[kPa]	0	0	0.00
Int. pressure due to 100% filling (long)	[kPa]	0	0	0.00

Table 3.96: *Results of benchmark 3-09 for pipe nr. 2, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	55.83	55.83	0.00
σ_t	[N/mm^2]	42.33	42.33	0.00
$\sigma_{a;max}$	[N/mm^2]	98.16	98.16	0.00
$\sigma_{V;max}$	[N/mm^2]	98.16	98.16	0.00

Table 3.97: *Results of benchmark 3-09 for pipe nr. 2, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	63.81	63.81	0.00
σ_t	[N/mm^2]	91.14	91.14	0.00
$\sigma_{a;max}$	[N/mm^2]	154.95	154.95	0.00
λ	[mm^{-1}]	0.000831	0.000831	0.00
q_r	[N/mm^2]	0.02618	0.02618	0.00
σ_{qr}	[N/mm^2]	0.51	0.51	0.00
$\sigma_{t;max}$	[N/mm^2]	0.51	0.51	0.00
$\sigma_{V;max}$	[N/mm^2]	155.21	155.2	0.01

Table 3.98: *Results of benchmark 3-09 for pipe nr. 2, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	1.66	1.66	0.00
σ_{px}	[N/mm^2]	0.83	0.83	0.00
σ_{ptest}	[N/mm^2]	2.69	2.69	0.00
σ_{pm}	[N/mm^2]	1.44	1.44	0.00

Table 3.99: *Results of benchmark 3-09 for pipe nr. 2, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	63.81	63.81	0.00
$\sigma_{a;max}$	[N/mm^2]	63.81	63.81	0.00
σ_{qr}	[N/mm^2]	0.51	0.51	0.00
σ_{qn}	[N/mm^2]	4.06	4.06	0.00
$\sigma_{t;max}$	[N/mm^2]	4.57	4.57	0.00
$\sigma_{V;max}$	[N/mm^2]	66.21	66.21	0.00

Table 3.100: *Results of benchmark 3-09 for pipe nr. 2, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	63.81	63.81	0.00
σ_{py}	[N/mm^2]	1.96	1.96	0.00
σ_{px}	[N/mm^2]	0.98	0.98	0.00
σ_{ptest}	[N/mm^2]	2.69	2.69	0.00
σ_{ptemp}	[N/mm^2]	11.56	11.56	0.00
$\sigma_{a;max}$	[N/mm^2]	64.79	64.79	0.00
σ_{qr}	[N/mm^2]	0.51	0.51	0.00
σ_{qn}	[N/mm^2]	4.06	4.06	0.00
$\sigma_{V;max}$	[N/mm^2]	66.27	66.27	0.00

Table 3.101: *Results of benchmark 3-09 for pipe nr. 2, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	350	350	0.00
σ_{py}	[N/mm^2]	320.83	320.83	0.00
σ_{pm}	[N/mm^2]	352.92	352.92	0.00
$\sigma_{V;max}$	[N/mm^2]	545.42	545.42	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.102: *Results of benchmark 3-09 for pipe nr. 2, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	0	0	0.00
Max. allowable	[mm]	37.2	37.2	0.00
Max. allow. (piggability)	[mm]	17.5	17.5	0.00

Table 3.103: *Results of benchmark 3-09 for pipe nr. 2, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Table 3.104: *Results of benchmark 3-09 for pipe nr. 3, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.31	0.31	0.00
σ_t	[N/mm^2]	6.7	6.7	0.00
$\sigma_{a;max}$	[N/mm^2]	6.85	6.85	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.105: *Results of benchmark 3-09 for pipe nr. 3, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.35	0.35	0.00
σ_t	[N/mm^2]	58.42	58.42	0.00
$\sigma_{a;max}$	[N/mm^2]	58.6	58.6	0.00
λ	[mm^{-1}]	0.002253	0.002253	0.00
q_r	[N/mm^2]	0.0029	0.0029	0.00
σ_{qr}	[N/mm^2]	0.11	0.11	0.00
$\sigma_{t;max}$	[N/mm^2]	0.11	0.11	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.106: *Results of benchmark 3-09 for pipe nr. 3, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	3.17	3.17	0.00
σ_{px}	[N/mm^2]	1.59	1.59	0.00
σ_{ptest}	[N/mm^2]	3.49	3.49	0.00
σ_{pm}	[N/mm^2]	2.75	2.75	0.00

Table 3.107: *Results of benchmark 3-09 for pipe nr. 3, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.09	0.09	0.00
$\sigma_{a;max}$	[N/mm^2]	0.04	0.04	0.00
σ_{qr}	[N/mm^2]	0.05	0.05	0.00
σ_{qn}	[N/mm^2]	6.05	6.05	0.00
$\sigma_{t;max}$	[N/mm^2]	3.05	3.05	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.108: *Results of benchmark 3-09 for pipe nr. 3, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.09	0.09	0.00
σ_{py}	[N/mm^2]	3.17	3.17	0.00
σ_{px}	[N/mm^2]	1.59	1.59	0.00
σ_{ptest}	[N/mm^2]	3.49	3.49	0.00
σ_{ptemp}	[N/mm^2]	0.32	0.32	0.00
$\sigma_{a;max}$	[N/mm^2]	1.63	1.63	0.00
σ_{qr}	[N/mm^2]	0.05	0.05	0.00
σ_{qn}	[N/mm^2]	6.05	6.05	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.109: *Results of benchmark 3-09 for pipe nr. 3, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	8	8	0.00
σ_{py}	[N/mm^2]	6.4	6.4	0.00
σ_{pm}	[N/mm^2]	n.a.	n.a.	
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (short)	[N/mm^2]	8	8	0.00
$\sigma_{a/t}$ (long)	[N/mm^2]	6.4	6.4	0.00

Table 3.110: *Results of benchmark 3-09 for pipe nr. 3, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	11.7	11.7	0.00
Max. allowable	[mm]	28.4	28.4	0.00
Max. allow. (piggability)	[mm]	19.9	19.9	0.00

Table 3.111: *Results of benchmark 3-09 for pipe nr. 3, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	713.89	713.89	0.00
Max. allow. external pressure (long)	[kPa]	89.24	89.24	0.00
Int. pressure due to 100% filling (short)	[kPa]	0	0	0.00
Int. pressure due to 100% filling (long)	[kPa]	0	0	0.00

Table 3.112: *Results of benchmark 3-09 for pipe nr. 4, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	116.46	116.46	0.00
σ_t	[N/mm^2]	45.18	45.18	0.00
$\sigma_{a;max}$	[N/mm^2]	161.63	161.63	0.00
$\sigma_{V;max}$	[N/mm^2]	161.63	161.63	0.00

Table 3.113: *Results of benchmark 3-09 for pipe nr. 4, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	133.09	133.09	0.00
σ_t	[N/mm^2]	97.28	97.28	0.00
$\sigma_{a;max}$	[N/mm^2]	230.38	230.38	0.00
λ	[mm^{-1}]	0.000569	0.000569	0.00
q_r	[N/mm^2]	0.02927	0.02927	0.00
σ_{qr}	[N/mm^2]	14.51	14.51	0.00
$\sigma_{t;max}$	[N/mm^2]	14.51	14.51	0.00
$\sigma_{V;max}$	[N/mm^2]	237.96	238	0.02

Table 3.114: *Results of benchmark 3-09 for pipe nr. 4, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	12.2	12.2	0.00
σ_{px}	[N/mm^2]	6.1	6.1	0.00
σ_{ptest}	[N/mm^2]	16.23	16.23	0.00
σ_{pm}	[N/mm^2]	10.57	10.57	0.00

Table 3.115: *Results of benchmark 3-09 for pipe nr. 4, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	133.09	133.09	0.00
$\sigma_{a;max}$	[N/mm^2]	133.09	133.09	0.00
σ_{qr}	[N/mm^2]	14.51	14.51	0.00
σ_{qn}	[N/mm^2]	103.79	103.79	0.00
$\sigma_{t;max}$	[N/mm^2]	118.3	118.3	0.00
$\sigma_{V;max}$	[N/mm^2]	217.84	217.8	0.02

Table 3.116: *Results of benchmark 3-09 for pipe nr. 4, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	133.09	133.09	0.00
σ_{py}	[N/mm^2]	14.42	14.42	0.00
σ_{px}	[N/mm^2]	7.21	7.21	0.00
σ_{ptest}	[N/mm^2]	16.23	16.23	0.00
σ_{ptemp}	[N/mm^2]	23.12	23.12	0.00
$\sigma_{a;max}$	[N/mm^2]	140.31	140.31	0.00
σ_{qr}	[N/mm^2]	14.51	14.51	0.00
σ_{qn}	[N/mm^2]	103.79	103.79	0.00
$\sigma_{V;max}$	[N/mm^2]	216.05	216.1	0.02

Table 3.117: *Results of benchmark 3-09 for pipe nr. 4, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	342.86	342.86	0.00
σ_{py}	[N/mm^2]	327.27	327.27	0.00
σ_{pm}	[N/mm^2]	360	360	0.00
$\sigma_{V;max}$	[N/mm^2]	556.36	556.36	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.118: *Results of benchmark 3-09 for pipe nr. 4, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	2.4	2.4	0.00
Max. allowable	[mm]	77.7	77.7	0.00
Max. allow. (piggability)	[mm]	36.6	36.6	0.00

Table 3.119: *Results of benchmark 3-09 for pipe nr. 4, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Table 3.120: *Results of benchmark 3-09 for pipe nr. 5, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	223.5	223.5	0.00
σ_t	[N/mm^2]	50.9	50.9	0.00
$\sigma_{a;max}$	[N/mm^2]	274.41	274.41	0.00
$\sigma_{V;max}$	[N/mm^2]	274.41	274.41	0.00

Table 3.121: *Results of benchmark 3-09 for pipe nr. 5, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	255.43	255.43	0.00
σ_t	[N/mm^2]	109.61	109.61	0.00
$\sigma_{a;max}$	[N/mm^2]	365.04	365.04	0.00
λ	[mm^{-1}]	0.000239	0.000239	0.00
q_r	[N/mm^2]	0.07646	0.07646	0.00
σ_{qr}	[N/mm^2]	13.31	13.31	0.00
$\sigma_{t;max}$	[N/mm^2]	13.31	13.31	0.00
$\sigma_{V;max}$	[N/mm^2]	371.88	371.9	0.01

Table 3.122: *Results of benchmark 3-09 for pipe nr. 5, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	10.2	10.2	0.00
σ_{px}	[N/mm^2]	5.1	5.1	0.00
σ_{ptest}	[N/mm^2]	15.02	15.02	0.00
σ_{pm}	[N/mm^2]	8.83	8.83	0.00

Table 3.123: *Results of benchmark 3-09 for pipe nr. 5, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	255.43	255.43	0.00
$\sigma_{a;max}$	[N/mm^2]	255.43	255.43	0.00
σ_{qr}	[N/mm^2]	13.31	13.31	0.00
σ_{qn}	[N/mm^2]	44.12	44.17	0.11
$\sigma_{t;max}$	[N/mm^2]	57.43	57.48	0.09
$\sigma_{V;max}$	[N/mm^2]	288.47	288.5	0.01

Table 3.124: *Results of benchmark 3-09 for pipe nr. 5, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	255.43	255.43	0.00
σ_{py}	[N/mm^2]	12.06	12.06	0.00
σ_{px}	[N/mm^2]	6.03	6.03	0.00
σ_{ptest}	[N/mm^2]	15.02	15.02	0.00
σ_{ptemp}	[N/mm^2]	25.34	25.34	0.00
$\sigma_{a;max}$	[N/mm^2]	261.46	261.46	0.00
σ_{qr}	[N/mm^2]	13.31	13.31	0.00
σ_{qn}	[N/mm^2]	44.12	44.17	0.11
$\sigma_{V;max}$	[N/mm^2]	287.87	287.9	0.01

Table 3.125: *Results of benchmark 3-09 for pipe nr. 5, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	173.91	173.91	0.00
σ_{py}	[N/mm^2]	153.85	153.85	0.00
σ_{pm}	[N/mm^2]	169.23	169.23	0.00
$\sigma_{V;max}$	[N/mm^2]	261.54	261.54	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.126: *Results of benchmark 3-09 for pipe nr. 5, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	1.8	1.8	0.00
Max. allowable	[mm]	170	170	0.00
Max. allow. (piggability)	[mm]	80	80	0.00

Table 3.127: *Results of benchmark 3-09 for pipe nr. 5, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Use D-GEO PIPELINE input file bm3-9.dri to run this benchmark.

3.10 HDD with 3D geometry – Bundled pipeline (2 PE pipes)

3.10.1 Description

The same input as for benchmark 3-7a (section 3.7) is used except that five pipes are used instead of one. Their characteristics are given in the table below.

Table 3.128: *Pipe material data (benchmark 3-10)*

		PE80	**PE100**
Material		Synthetic	Synthetic
E_{b}	[N/mm^2]	1000	1200
$E_{pipe;long}$	[N/mm^2]	200	300
R_{eb}	[N/mm^2]	8	10
$R_{eb;long}$	[N/mm^2]	6.3	8
α	[-]	0.65	0.5
D_0	[mm]	50	355
d_{n}	[mm]	3.7	26.1
γ_{b}	[kN/m^3]	9.54	13
p_{d}	[Bar]	3	5
p_{t}	[Bar]	6	5.5
ΔT	[°C]	5	6

3.10.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Strength calculation for bundled pipelines

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter “Strength pipeline calculation” in the Background section of the User Manual of D-GEO PIPELINE. The properties of the equivalent pipe are:

D_{eq}	[mm]	328.96
$d_{n;eq}$	[mm]	29.21
γ_{eq}	[kN/m^3]	12.93
I_{eq}	[m^4]	0.00031187
E_{eq}	[N/mm^2]	1412.43
$k_{V;max;eq}$	[kN/m^3]	133262.93

The total pulling force is the contribution of five components. Results are given in the tables below for the equivalent pipeline and for the 2 single pipelines.

Table 3.129: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-10) for the equivalent pipe*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	166.76	0	0	0	0	166.76
2	43.04	162.75	26.49	0	0	0	189.25
3	338	135.27	0	181.59	0.46	23.35	367.16
4	403.91	129.13	40.58	0	0	0	401.6
5	648.25	106.36	0	151.28	48.58	0	578.69
6	769.54	95.06	74.67	0	0	0	642.06
7	1293.14	46.28	0	322.94	121.04	0	1037.25
8	1440.63	32.53	90.8	0	0	0	1114.31
9	1715.52	6.92	0	169.23	0.57	85.16	1343.66
10	1789.79	0	45.72	0	0	0	1382.46

Table 3.130: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-10) for pipe nr. 1*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	2.6	0	0	0	0	2.6
2	43.04	2.54	2.6	0	0	0	5.14
3	338	2.11	0	17.83	0	1.53	24.08
4	403.91	2.02	3.98	0	0	0	27.97
5	648.25	1.66	0	14.77	3.66	0	46.05
6	769.54	1.48	7.33	0	0	0	53.21
7	1293.14	0.72	0	31.65	10.66	0	94.76
8	1440.63	0.51	8.92	0	0	0	103.46
9	1715.52	0.11	0	16.62	0	8.25	127.93
10	1789.79	0	4.49	0	0	0	132.31

Table 3.131: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-10) for pipe nr. 2*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	164.16	0	0	0	0	164.16
2	43.04	160.21	27.49	0	0	0	187.7
3	338	133.16	0	188.42	0.46	23.74	373.27
4	403.91	127.11	42.1	0	0	0	409.33
5	648.25	104.7	0	156.95	49.7	0	593.56
6	769.54	93.58	77.47	0	0	0	659.91
7	1293.14	45.55	0	335.07	124.81	0	1071.77
8	1440.63	32.03	94.21	0	0	0	1152.45
9	1715.52	6.81	0	175.59	0.57	88.3	1391.71
10	1789.79	0	47.44	0	0	0	1432.33

3.10.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.132: *Results of benchmark 3-10, Buoyancy control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	131	131	0.00
Weight of pipeline (incl. filling)	[kg/m]	47	47	0.00
Effective weight of pipe	[kg/m]	85	85	0.00

Table 3.133: *Results of benchmark 3-10, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	167	0	167	0.00	0.00
T2	43	189	43	189	0.00	0.00
T3	338	367	338	367	0.00	0.00
T4	1441	1114	1441	1114	0.00	0.00
T5	1716	1344	1716	1344	0.00	0.00
T6	1790	1382	1790	1382	0.00	0.00
Max. rep. pulling force	-	4	-	4	-	0.00

Use D-GEO PIPELINE input file bm3-10.dri to run this benchmark.

3.11 HDD with 3D geometry – Bundled pipeline (3 steel pipes)

3.11.1 Description

The same input as for benchmark 3-7a (section 3.7) is used except that five pipes are used instead of one. Their characteristics are given in the table below.

Table 3.134: *Pipe material data (benchmark 3-11)*

		FE385	**FE360**	**Steel 1**
Material		Steel	Steel	Steel
δ_t	[%]	10	15	25
E_b	[N/mm^2]	205800	205800	180500
R_{eb}	[N/mm^2]	385	360	200
γ_m	[-]	1.2	1.1	1.3
$\gamma_{m;test}$	[-]	1.1	1.05	1.15
D_0	[mm]	219.1	457	1000
d_n	[mm]	22.2	9.52	35
γ_b	[kN/m^3]	85	78.5	65
p_d	[Bar]	3	4	5
p_t	[Bar]	6	6.5	9
ΔT	[°C]	4	8	10

3.11.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Strength calculation for bundled pipelines

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter “Strength pipeline calculation” in the Background section of the User Manual of D-GEO PIPELINE [Deltares]. The properties of the equivalent pipe are:

D_{eq}	[mm]	1205.49
$d_{n;eq}$	[mm]	36.27
γ_{eq}	[kN/m^3]	68.42
I_{eq}	[m^4]	0.0227877
E_{eq}	[N/mm^2]	101597.36
$k_{V;max;eq}$	[kN/m^3]	25604.32

The total pulling force is the contribution of five components. Results are given in the tables below for the equivalent pipeline and for the 3 single steel pipelines.

Table 3.135: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-11) for the equivalent pipe*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	3721.21	0	0	0	0	3721.21
2	43.04	3631.73	88.51	0	0	0	3720.24
3	338	3018.47	0	606.62	338.05	275.2	4326.85
4	403.91	2881.43	135.55	0	0	0	4325.36
5	648.25	2373.4	0	1130.34	515.78	0	5463.45
6	769.54	2121.23	249.44	0	0	0	5460.71
7	1293.14	1032.6	0	1516.31	915.32	0	6803.71
8	1440.63	725.95	303.33	0	0	0	6800.39
9	1715.52	154.41	0	565.34	418.54	369.21	7581.95
10	1789.79	0	152.74	0	0	0	7580.28

Table 3.136: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-11) for pipe nr. 1*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	430.7	0	0	0	0	430.7
2	43.04	420.34	19.57	0	0	0	439.92
3	338	349.36	0	134.16	7.01	34.65	544.75
4	403.91	333.5	29.98	0	0	0	558.87
5	648.25	274.7	0	124.15	62.31	0	686.52
6	769.54	245.52	55.16	0	0	0	712.5
7	1293.14	119.52	0	247.26	120.77	0	954.53
8	1440.63	84.02	67.08	0	0	0	986.12
9	1715.52	17.87	0	125.03	8.67	66.45	1120.12
10	1789.79	0	33.78	0	0	0	1136.03

Table 3.137: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-11) for pipe nr. 2*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	456.95	0	0	0	0	456.95
2	43.04	445.96	32.68	0	0	0	478.64
3	338	370.66	0	223.95	23.85	44.23	695.36
4	403.91	353.83	50.04	0	0	0	728.57
5	648.25	291.44	0	229.82	86.94	0	982.95
6	769.54	260.48	92.09	0	0	0	1044.07
7	1293.14	126.8	0	428.55	187.44	0	1526.37
8	1440.63	89.14	111.98	0	0	0	1600.7
9	1715.52	18.96	0	208.71	29.53	111.14	1879.89
10	1789.79	0	56.39	0	0	0	1917.32

Table 3.138: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-11) for pipe nr. 3*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	2833.56	0	0	0	0	2833.56
2	43.04	2765.42	76.94	0	0	0	2842.36
3	338	2298.45	0	527.34	324.47	219.2	3446.4
4	403.91	2194.1	117.84	0	0	0	3459.89
5	648.25	1807.25	0	1039.44	425.87	0	4538.35
6	769.54	1615.24	216.84	0	0	0	4563.17
7	1293.14	786.29	0	1357.92	782.44	0	5874.58
8	1440.63	552.78	263.69	0	0	0	5904.76
9	1715.52	117.58	0	491.46	401.73	323.45	6686.2
10	1789.79	0	132.78	0	0	0	6701.4

3.11.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.139: *Results of benchmark 3-11, Buoyancy control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	1283	1283	0.00
Weight of pipeline (incl. filling)	[kg/m]	1040	1040	0.00
Effective weight of pipe	[kg/m]	244	244	0.00

Table 3.140: *Results of benchmark 3-11, Pulling forces in the pipeline*

	Benchmark		D-GEO PIPELINE		Relative error	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	3721	0	3721	0.00	0.00
T2	43	3720	43	3720	0.00	0.00
T3	338	4327	338	4327	0.00	0.00
T4	1441	6800	1441	6800	0.00	0.00
T5	1716	7582	1716	7582	0.00	0.00
T6	1790	7580	1790	7580	0.00	0.00
Max. rep. pulling force	-	6493	-	6493	-	0.00

Use D-GEO PIPELINE input file bm3-11.dri to run this benchmark.

3.12 Micro tunneling with 3D geometry – Steel pipe

3.12.1 Description

The same input data's as for benchmark 3-7 (section 3.7) are used except that the calculation is performed for micro tunneling instead of horizontal directional drilling. Few input values must be added compare to HDD calculation:

Friction with injection of lubricant	7.5	[kPa]
Friction without injection of lubricant	10	[kPa]
Allowable thrust force	200	[kN]
Volume loss for surface settlement	15	[%]

Two cases are checked:

- ◇ Case A (bm3-12a): thrusting direction from left to right;
- ◇ Case B (bm3-12b): thrusting direction from right to left.

3.12.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Soil mechanical data

The soil mechanical data's are determined using the formulas given in chapter "Calculation of soil mechanical data" in the Background section of the User Manual of D-GEO PIPELINE.

Operation Parameters

The face support pressures, the thrust forces and the uplift safety factor are determined using the formulas given in chapter “Micro Tunneling” in the Background section of the User Manual of D-GEO PIPELINE. Intermediate results are given in the tables below.

Table 3.141: *Analytical results for the calculation of the face support pressures*

Vert.	σ_v'	u	C/D	β	O/A	α	K	K_{A3}	Q_s
[-]	[kN/m^2]	[kN/m^2]	[-]	[-]	[-]	[-]	[-]	[-]	[kN/m^2]
1	25.396	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2	27.34	116.373	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
3	120.537	192.742	3.199	66.706	6.645	1.432	0.417	0.214	3.376
4	162.667	218.871	6.643	66.706	6.645	1.465	0.417	0.212	3.842
5	448.99	352.192	21.924	68.683	7.125	1.489	0.349	0.167	9.702
6	353.117	250.214	7.226	68.683	7.125	1.468	0.349	0.168	9.343
7	161.58	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
8	89.894	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 3.142: *Analytical results for the calculation of the uplift safety factor*

Vert.	Part dry	g_{uplift}	g_{weight}	f_{uplift}
[-]	[%]	[kN/m^2]	[kN/m^2]	[-]
1	100	0	6.897	999
2	0	7.854	6.897	4.009
3	0	7.854	6.897	15.493
4	0	7.854	6.897	20.858
5	0	7.854	6.897	57.269
6	0	7.854	6.897	45.074
7	66.256	2.65	6.897	61.495
8	100	0	6.897	999

3.12.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.143: *Results of benchmark 3-12a, Vertical soil stresses*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	32	21	21	32	21	21	0.00	0.00	0.00
2	106	25	45	106	25	45	0.00	0.00	0.00
3	830	116	79	830	116	79	0.00	0.00	0.00
4	1048	158	90	1048	158	90	0.00	0.00	0.00
5	2010	444	109	2010	444	109	0.00	0.00	0.00
6	1615	348	113	1615	348	141	0.00	0.00	19.86
7	284	157	102	284	157	102	0.00	0.00	0.00
8	213	85	85	213	85	85	0.00	0.00	0.00

Table 3.144: *Results of benchmark 3-12a, Neutral horizontal soil stress and bearing capacities*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	16	455	208	16	455	208	0.00	0.00	0.00
2	19	494	147	19	494	147	0.00	0.00	0.00
3	58	3315	1715	58	3315	1715	0.00	0.00	0.00
4	79	4434	2364	79	4435	2364	0.00	0.02	0.00
5	189	21114	12962	189	21114	12962	0.00	0.00	0.00
6	149	16630	8152	149	16630	8152	0.00	0.00	0.00
7	116	1240	702	116	1240	702	0.00	0.00	0.00
8	63	838	451	63	838	451	0.00	0.00	0.00

Table 3.145: *Results of benchmark 3-12a, Vertical and horizontal moduli of subgrade reaction*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h
[-]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[%]	[%]	[%]
1	371	303	212	371	303	212	0.00	0.00	0.00
2	253	544	380	253	544	380	0.00	0.00	0.00
3	9424	17421	12195	9424	17421	12195	0.00	0.00	0.00
4	16574	18611	13028	16574	18611	13028	0.00	0.00	0.00
5	12499	13305	9313	12499	13305	9313	0.00	0.00	0.00
6	16911	11410	7987	16911	11410	7987	0.00	0.00	0.00
7	254	367	257	254	367	257	0.00	0.00	0.00
8	327	260	182	327	260	182	0.00	0.00	0.00

Table 3.146: *Results of benchmark 3-12a, Maximal axial friction and displacements*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}
[-]	[kN/m^2]	[mm]	[mm]	[kN/m^2]	[mm]	[mm]	[%]	[%]	[%]
1	17	5	12	17	5	12	0.00	0.00	0.00
2	19	10	12	19	10	12	0.00	0.00	0.00
3	25	20	5	25	20	5	0.00	0.00	0.00
4	27	40	5	27	40	5	0.00	0.00	0.00
5	35	80	2	35	80	2	0.00	0.00	0.00
6	33	60	2	36	60	2	8.33	0.00	0.00
7	32	50	12	32	50	12	0.00	0.00	0.00
8	27	35	12	27	35	12	0.00	0.00	0.00

Table 3.147: *Results of benchmark 3-12a, Face support pressures*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	P_{max}	P_{min}	P_{target}	P_{max}	P_{min}	P_{target}	P_{max}	P_{min}	P_{target}
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	21	0	19	21	0	19	0.00	0.00	0.00
2	120	128	137	120	128	137	0.00	0.00	0.00
3	261	248	253	261	248	253	0.00	0.00	0.00
4	318	242	300	318	242	300	0.00	0.00	0.00
5	668	390	544	668	389	544	0.00	0.26	0.00
6	503	277	401	503	276	401	0.00	0.36	0.00
7	135	0	120	135	0	120	0.00	0.00	0.00
8	75	0	67	75	0	67	0.00	0.00	0.00

Table 3.148: *Results of benchmark 3-12a, Thrust forces*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Vert.	$F_{\text{lubricated}}$	F_{normal}	$F_{\text{lubricated}}$	F_{normal}	$F_{\text{lubricated}}$	F_{normal}
[-]	[kN]	[kN]	[kN]	[kN]	[%]	[%]
1	337	498	337	498	0.00	0.00
2	1719	2525	1719	2525	0.00	0.00
3	3414	5021	3414	5021	0.00	0.00
4	4089	6015	4089	6015	0.00	0.00
5	30386	45366	30386	45366	0.00	0.00
6	50715	75915	50715	75915	0.00	0.00
7	54517	81728	54517	81728	0.00	0.00
8	55288	82906	55288	82906	0.00	0.00

Table 3.149: *Results of benchmark 3-12b, Thrust forces*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Vert.	$F_{\text{lubricated}}$	F_{normal}	$F_{\text{lubricated}}$	F_{normal}	$F_{\text{lubricated}}$	F_{normal}
[-]	[kN]	[kN]	[kN]	[kN]	[%]	[%]
1	55920	83873	55920	83873	0.00	0.00
2	54723	82031	54723	82031	0.00	0.00
3	53211	79718	53211	79718	0.00	0.00
4	52611	78798	52611	78798	0.00	0.00
5	26696	39830	26696	39830	0.00	0.00
6	6142	9056	6142	9056	0.00	0.00
7	1899	2802	1899	2802	0.00	0.00
8	1044	1540	1044	1540	0.00	0.00

Table 3.150: *Results of benchmark 3-12a, Uplift safety factor*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Vert.	Calculated	Required	Calculated	Required	Calculated	Required
[-]	[-]	[-]	[-]	[-]	[%]	[%]
1	n.a.	1.15	999	1.15		0.00
2	4.01	1.15	4	1.15	0.25	0.00
3	15.49	1.15	15.48	1.15	0.06	0.00
4	20.86	1.15	20.85	1.15	0.05	0.00
5	57.27	1.15	57.27	1.15	0.00	0.00
6	45.07	1.15	45.07	1.15	0.00	0.00
7	61.49	1.15	57.7	1.15	6.57	0.00
8	n.a.	1.15	999	1.15		0.00

Table 3.151: *Results of benchmark 3-12a, Trough*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
	f_{trough}	Trough	Depth	f_{trough}	Trough	Depth	f_{trough}	Trough	Depth
	[-]	[-]	[m]	[-]	[-]	[m]	[%]	[%]	[%]
v1	0.02156	2.093	2.309	0.02156	2.093	2.309	0.00	0.00	0.00
v2	0.00746	6.052	11.516	0.00746	6.052	11.516	0.00	0.00	0.00
v3	0.00433	10.431	21.699	0.00433	10.431	21.699	0.00	0.00	0.00
v4	0.00376	12	25.349	0.00376	12	25.349	0.00	0.00	0.00
v5	0.00235	19.235	49.182	0.00235	19.235	49.182	0.00	0.00	0.00
v6	0.0026	17.349	41.18	0.0026	17.349	41.18	0.00	0.00	0.00
v7	0.00608	7.416	14.689	0.00608	7.416	14.689	0.00	0.00	0.00
v8	0.00978	4.614	8.172	0.00978	4.614	8.172	0.00	0.00	0.00

Table 3.152: *Results of benchmark 3-12a, Subsidence at different horizontal distances of Z axis (from 0 to 0.7W)*

	Benchmark [mm]					**D-GEO PIPELINE [mm]**					**Relative error [%]**				
	0	0.1	0.2	0.4	0.7	0	0.1	0.2	0.4	0.7	0	0.1	0.2	0.4	0.7
	$\times W$					$\times W$					$\times W$				
v1	22	21	21	20	16	22	21	21	20	16	0.0	0.0	0.0	0.0	0.0
v2	7	7	7	6	3	7	7	7	6	3	0.0	0.0	0.0	0.0	0.0
v3	4	4	4	3	1	4	4	4	3	1	0.0	0.0	0.0	0.0	0.0
v4	4	4	3	3	1	4	4	3	3	1	0.0	0.0	0.0	0.0	0.0
v5	2	2	2	1	0	2	2	2	1	0	0.0	0.0	0.0	0.0	0.0
v6	3	3	2	2	1	3	3	2	2	1	0.0	0.0	0.0	0.0	0.0
v7	6	6	6	4	2	6	6	6	4	2	0.0	0.0	0.0	0.0	0.0
v8	10	10	9	8	5	10	10	9	8	5	0.0	0.0	0.0	0.0	0.0

Table 3.153: *Results of benchmark 3-12a, Subsidence at different horizontal distances of Z axis (from 1W to 2.5W)*

	Benchmark [mm]					**D-GEO PIPELINE [mm]**					**Relative error [%]**				
	1	1.3	1.6	2	2.5	1	1.3	1.6	2	2.5	1	1.3	1.6	2	2.5
	$\times W$					$\times W$					$\times W$				
v1	12	8	5	2	0	12	8	5	2	0	0.0	0.0	0.0	0.0	0.0
v2	1	0	0	0	0	1	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v3	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v4	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v5	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v6	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v7	1	0	0	0	0	1	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v8	2	1	0	0	0	2	1	0	0	0	0.0	0.0	0.0	0.0	0.0

Use D-GEO PIPELINE input files bm3-12a.dri and bm3-12b.dri to run this benchmark.

3.13 Micro tunneling with 3D geometry – Synthetic pipe

3.13.1 Description

The same input data's as for benchmark 3-12a (section 3.12) are used except that a synthetic pipe (with a Young's modulus at short term of 30000 kPa) instead of a steel pipe is used. Results are expected to be the same as bm3-12a except for the moduli of subgrade reaction.

3.13.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Soil mechanical data

The moduli of subgrade reaction are determined using the formulas given in chapter "Calculation of soil mechanical data" in the Background section of the User Manual of D-GEO PIPELINE.

3.13.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the table below can be found in the *Report*.

Table 3.154: *Results of benchmark 3-13, Vertical and horizontal moduli of subgrade reaction*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h
[-]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[%]	[%]	[%]
1	405	331	232	405	331	232	0.00	0.00	0.00
2	277	594	416	277	594	416	0.00	0.00	0.00
3	10477	19458	13620	10477	19458	13620	0.00	0.00	0.00
4	18504	20827	14579	18504	20827	14579	0.00	0.00	0.00
5	13924	14829	10380	13924	14829	10380	0.00	0.00	0.00
6	18883	12703	8892	18883	12703	8892	0.00	0.00	0.00
7	278	402	281	278	402	281	0.00	0.00	0.00
8	358	285	199	358	285	199	0.00	0.00	0.00

Use D-GEO PIPELINE input file bm3-13.dri to run this benchmark.

3.14 Micro tunneling with 3D geometry – Concrete pipe

3.14.1 Description

The same input data's as for benchmark 3-12a (section 3.12) are used except that a concrete pipe instead of a steel pipe is used, but the properties are the same. Therefore, results are expected to be the same as bm3-12a.

3.14.2 Analytical results

The same Excel spreadsheet as for benchmark 3-12a (section 3.12) is used.

3.14.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report* and are identical to the results of benchmark 3-12a (section 3.12) .

Table 3.155: *Results of benchmark 3-14, Vertical soil stresses*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$	$q_{v;p}$	$q_{v;n}$	$q_{v;r;n}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	32	21	21	32	21	21	0.00	0.00	0.00
2	106	25	45	106	25	45	0.00	0.00	0.00
3	830	116	79	830	116	79	0.00	0.00	0.00
4	1048	158	90	1048	158	90	0.00	0.00	0.00
5	2010	444	109	2010	444	109	0.00	0.00	0.00
6	1615	348	113	1615	348	141	0.00	0.00	19.86
7	284	157	102	284	157	102	0.00	0.00	0.00
8	213	85	85	213	85	85	0.00	0.00	0.00

Table 3.156: *Results of benchmark 3-14, Neutral horizontal soil stress and bearing capacities*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$	$q_{h;n}$	$P_{v;e}$	$P_{h;e}$
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	16	455	208	16	455	208	0.00	0.00	0.00
2	19	494	147	19	494	147	0.00	0.00	0.00
3	58	3315	1715	58	3315	1715	0.00	0.00	0.00
4	79	4434	2364	79	4435	2364	0.00	0.02	0.00
5	189	21114	12962	189	21114	12962	0.00	0.00	0.00
6	149	16630	8152	149	16630	8152	0.00	0.00	0.00
7	116	1240	702	116	1240	702	0.00	0.00	0.00
8	63	838	451	63	838	451	0.00	0.00	0.00

Table 3.157: *Results of benchmark 3-14, Vertical and horizontal moduli of subgrade reaction*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h	$k_{v;top}$	$k_{v;bot}$	k_h
[-]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[%]	[%]	[%]
1	371	303	212	371	303	212	0.00	0.00	0.00
2	253	544	380	253	544	380	0.00	0.00	0.00
3	9424	17421	12195	9424	17421	12195	0.00	0.00	0.00
4	16574	18611	13028	16574	18611	13028	0.00	0.00	0.00
5	12499	13305	9313	12499	13305	9313	0.00	0.00	0.00
6	16911	11410	7987	16911	11410	7987	0.00	0.00	0.00
7	254	367	257	254	367	257	0.00	0.00	0.00
8	327	260	182	327	260	182	0.00	0.00	0.00

Table 3.158: *Results of benchmark 3-14, Maximal axial friction and displacements*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}
[-]	[kN/m^2]	[mm]	[mm]	[kN/m^2]	[mm]	[mm]	[%]	[%]	[%]
1	16.83	5	12	17	5	12	0.00	0.00	0.00
2	18.93	10	12	19	10	12	0.00	0.00	0.00
3	24.55	20	5	25	20	5	0.00	0.00	0.00
4	26.97	40	5	27	40	5	0.00	0.00	0.00
5	35.39	80	2	35	80	2	0.00	0.00	0.00
6	33.21	60	2	36	60	2	8.33	0.00	0.00
7	32.4	50	12	32	50	12	0.00	0.00	0.00
8	26.77	35	12	27	35	12	0.00	0.00	0.00

Table 3.159: *Results of benchmark 3-14, Face support pressures*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
Vert.	P_{max}	P_{min}	P_{target}	P_{max}	P_{min}	P_{target}	P_{max}	P_{min}	P_{target}
[-]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
1	21	0	19	21	0	19	0.00	0.00	0.00
2	120	128	137	120	128	137	0.00	0.00	0.00
3	261	248	253	261	248	253	0.00	0.00	0.00
4	318	242	300	318	242	300	0.00	0.00	0.00
5	668	390	544	668	389	544	0.00	0.26	0.00
6	503	277	401	503	276	401	0.00	0.36	0.00
7	135	0	120	135	0	120	0.00	0.00	0.00
8	75	0	67	75	0	67	0.00	0.00	0.00

Table 3.160: *Results of benchmark 3-14, Thrust forces*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Vert.	$F_{\text{lubricated}}$	F_{normal}	$F_{\text{lubricated}}$	F_{normal}	$F_{\text{lubricated}}$	F_{normal}
[-]	[kN]	[kN]	[kN]	[kN]	[%]	[%]
1	337	498	337	498	0.00	0.00
2	1719	2525	1719	2525	0.00	0.00
3	3414	5021	3414	5021	0.00	0.00
4	4089	6015	4089	6015	0.00	0.00
5	30386	45366	30386	45366	0.00	0.00
6	50715	75915	50715	75915	0.00	0.00
7	54517	81728	54517	81728	0.00	0.00
8	55288	82906	55288	82906	0.00	0.00

Table 3.161: *Results of benchmark 3-14, Uplift safety factor*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Vert.	Calculated	Required	Calculated	Required	Calculated	Required
[-]	[-]	[-]	[-]	[-]	[%]	[%]
1	999	1.15	999	1.15	0.00	0.00
2	4.01	1.15	4	1.15	0.25	0.00
3	15.49	1.15	15.48	1.15	0.06	0.00
4	20.86	1.15	20.85	1.15	0.05	0.00
5	57.27	1.15	57.27	1.15	0.00	0.00
6	45.07	1.15	45.07	1.15	0.00	0.00
7	61.49	1.15	57.7	1.15	6.57	0.00
8	999	1.15	999	1.15	0.00	0.00

Table 3.162: *Results of benchmark 3-14, Trough*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
	f_{trough}	Trough	Depth	f_{trough}	Trough	Depth	f_{trough}	Trough	Depth
	[-]	[-]	[m]	[-]	[-]	[m]	[%]	[%]	[%]
v1	0.02156	2.093	2.309	0.02156	2.093	2.309	0.00	0.00	0.00
v2	0.00746	6.052	11.516	0.00746	6.052	11.516	0.00	0.00	0.00
v3	0.00433	10.431	21.699	0.00433	10.431	21.699	0.00	0.00	0.00
v4	0.00376	12	25.349	0.00376	12	25.349	0.00	0.00	0.00
v5	0.00235	19.235	49.182	0.00235	19.235	49.182	0.00	0.00	0.00
v6	0.0026	17.349	41.18	0.0026	17.349	41.18	0.00	0.00	0.00
v7	0.00608	7.416	14.689	0.00608	7.416	14.689	0.00	0.00	0.00
v8	0.00978	4.614	8.172	0.00978	4.614	8.172	0.00	0.00	0.00

Table 3.163: *Results of benchmark 3-14, Subsidence at different horizontal distances of Z axe (from 0 to 0.7W)*

	Benchmark [mm]					**D-GEO PIPELINE [mm]**					**Relative error [%]**				
	0	0.1	0.2	0.4	0.7	0	0.1	0.2	0.4	0.7	0	0.1	0.2	0.4	0.7
	$\times W$					$\times W$					$\times W$				
v1	22	21	21	20	16	22	21	21	20	16	0.0	0.0	0.0	0.0	0.0
v2	7	7	7	6	3	7	7	7	6	3	0.0	0.0	0.0	0.0	0.0
v3	4	4	4	3	1	4	4	4	3	1	0.0	0.0	0.0	0.0	0.0
v4	4	4	3	3	1	4	4	3	3	1	0.0	0.0	0.0	0.0	0.0
v5	2	2	2	1	0	2	2	2	1	0	0.0	0.0	0.0	0.0	0.0
v6	3	3	2	2	1	3	3	2	2	1	0.0	0.0	0.0	0.0	0.0
v7	6	6	6	4	2	6	6	6	4	2	0.0	0.0	0.0	0.0	0.0
v8	10	10	9	8	5	10	10	9	8	5	0.0	0.0	0.0	0.0	0.0

Table 3.164: *Results of benchmark 3-14, Subsidence at different horizontal distances of Z axe (from 1W to 2.5W)*

	Benchmark [mm]					**D-GEO PIPELINE [mm]**					**Relative error [%]**				
	1	1.3	1.6	2	2.5	1	1.3	1.6	2	2.5	1	1.3	1.6	2	2.5
	$\times W$					$\times W$					$\times W$				
v1	12	8	5	2	0	12	8	5	2	0	0.0	0.0	0.0	0.0	0.0
v2	1	0	0	0	0	1	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v3	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v4	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v5	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v6	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v7	1	0	0	0	0	1	0	0	0	0	0.0	0.0	0.0	0.0	0.0
v8	2	1	0	0	0	2	1	0	0	0	0.0	0.0	0.0	0.0	0.0

Use D-GEO PIPELINE input file bm3-14.dri to run this benchmark.

3.15 Trenching (3 sections) – 3D geometry in four layers – Compressible border above drainage border

3.15.1 Description

The same input data's as for benchmark 1-7 (section 3.7) are used except that a construction in trench is modeled. The trenching configuration (3 trench sections) is given in Table 3-114. Calculations are performed for 8 verticals with *L* coordinates of 70, 150, 400, 600, 900, 1200, 1500 and 1800 m. Six cases are considered depending on the type of filling of the trench:

- ◇ Case A (bm3-15a): sand poorly compacted;
- ◇ Case B (bm3-15b): stiff clay poorly compacted;
- ◇ Case C (bm3-15c): soft soil poorly compacted;
- ◇ Case D (bm3-15d): sand well compacted;
- ◇ Case E (bm3-15e): stiff clay well compacted;
- ◇ Case F (bm3-15f): soft soil well compacted.

The type of filling will influence only the actual soil stress.

Table 3.165: *Configuration of the 3 trench sections (benchmark 3-15a)*

		Trench 1	**Trench 2**	**Trench 3**
X_{begin}	[m]	50	400	1300
Y_{begin}	[m]	0	10	-6
Z_{begin}	[m]	-1	-4	-2
X_{end}	[m]	400	1300	1900
Y_{end}	[m]	10	-6	5
Z_{end}	[m]	-4	-2	0.5
E_b	[N/mm^2]	1500	2000	3500
D_0	[mm]	500	300	600
d_n	[mm]	35	20	50
γ_b	[kN/m^3]	78.5	90	56
Width	[mm]	550	400	700
Slope of the wall [1:x]	[-]	2	3	4
Offset	[m]	0.1	0.2	0.3

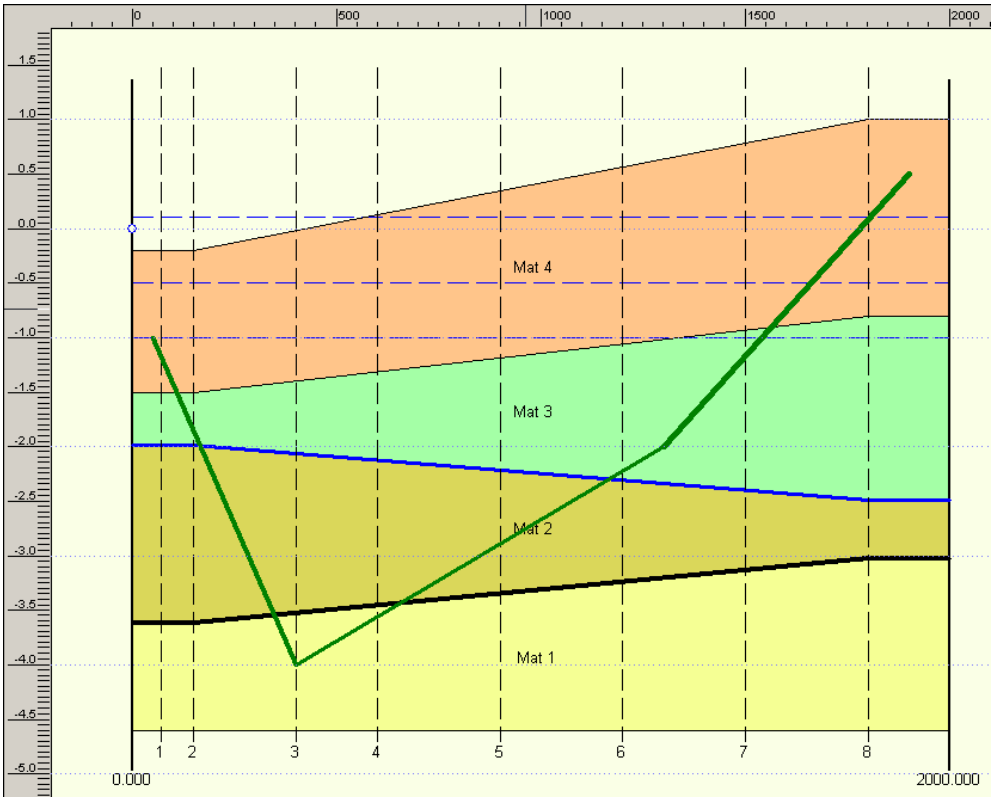

Figure 3.4: *Lateral view of the 3 trench sections (benchmark 3-15)*

3.15.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Soil mechanical data

The soil mechanical data's are determined using the formulas given in chapter "Calculation of soil mechanical data" in the Background section of the User Manual of D-GEO PIPELINE.

Operation Parameters

The safety factors for uplift and hydraulic heave are determined using the formulas given in chapter “Trench” in the Background section of the User Manual of D-GEO PIPELINE. Intermediate results are given in the tables below.

Table 3.166: *Analytical results for the calculation of the uplift safety factor*

Vert.	Part dry	$\sigma_{v;top}$'	q_{pipe}	q_{uplift}	f
[-]	[%]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[-]
1	0	0.367	4.014	1.963	2.138
2	0	4.458	4.014	1.963	3.179
3	0	30.326	4.014	1.963	9.767
4	0	27.931	1.583	0.707	14.094
5	0	23.082	1.583	0.707	12.036
6	0	19.085	1.583	0.707	10.34
7	0	12.564	4.838	2.827	4.377
8	100	6.774	4.838	0	999

Table 3.167: *Analytical results for the hydraulic heave check*

	a	b	$d_{2;d}$	f_{Bous}	σ_v	σ_{bot}	W_{bot}	W_{top}	W_w	u_{opw}	φ	f
	[m]	[m]	[m]	[-]	[kN/m^2]						[m]	[-]
v1	2.6	0.28	2.08	0.34	54.7	16.6	38.1	16.6	10.2	28.5	-0.8	1.9
v2	4	0.28	1.39	0.15	54.7	28.2	26.5	28.2	17.1	28.5	-0.8	1.7
v3	8.7	0.28	-0.84	-0.04	55.1	71.9	-16.8	71.9	38.5	27.7	-0.7	100
v4	12.1	0.2	-0.47	-0.01	55.4	64.7	-9.4	64.7	34.1	27.1	-0.7	100
v5	10.8	0.2	0.09	0	55.8	54.1	1.7	54.1	27.4	26.1	-0.7	1.1
v6	9.4	0.2	0.65	0.03	56.2	44	12.3	44	20.7	25.1	-0.7	1.4
v7	10.2	0.35	1.34	0.05	56.7	33.1	23.6	33.1	12.7	24.1	-0.7	1.6
v8	6.1	0.35	2.48	0.2	57.1	16.7	40.4	16.7	0.2	23.1	-0.7	1.9

3.15.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.168: *Results of benchmark 3-15a, Vertical and horizontal soil stresses*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
	$q_{v;p}$	$q_{v;n}$	$q_{h;n}$	$q_{v;p}$	$q_{v;n}$	$q_{h;n}$	$q_{v;p}$	$q_{v;n}$	$q_{h;n}$
	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
v1	1	1	0	1	1	0	0.00	0.00	0.00
v2	9	5	4	9	5	4	0.00	0.00	0.00
v3	99	31	13	99	31	13	0.00	0.00	0.00
v4	127	28	12	127	28	12	0.00	0.00	0.00
v5	95	23	12	95	23	12	0.00	0.00	0.00
v6	70	19	18	70	19	18	0.00	0.00	0.00
v7	23	13	13	23	13	13	0.00	0.00	0.00
v8	10	7	6	10	8	6	0.00	12.5	0.00

Table 3.169: *Results of benchmark 3-15a, Initial vertical stress q_k for sand poorly compacted*

Vertical nr.	**Benchmark**	**D-GEO PIPELINE**	**Relative error**
[-]	[kN/m^2]	[kN/m^2]	[%]
1	1	1	0.00
2	6	6	0.00
3	99	99	0.00
4	127	127	0.00
5	95	95	0.00
6	70	70	0.00
7	16	16	0.00
8	8	8	0.00

Table 3.170: *Results of benchmark 3-15b, Initial vertical stress q_k for stiff clay poorly compacted*

Vertical nr.	**Benchmark**	**D-GEO PIPELINE**	**Relative error**
[-]	[kN/m^2]	[kN/m^2]	[%]
1	1	1	0.00
2	8	8	0.00
3	99	99	0.00
4	127	127	0.00
5	95	95	0.00
6	70	70	0.00
7	19	19	0.00
8	9	9	0.00

Table 3.171: *Results of benchmark 3-15c, Initial vertical stress q_k for soft soil poorly compacted*

Vertical nr.	**Benchmark**	**D-GEO PIPELINE**	**Relative error**
[-]	[kN/m^2]	[kN/m^2]	[%]
1	1	1	0.00
2	9	9	0.00
3	99	99	0.00
4	127	127	0.00
5	95	95	0.00
6	70	70	0.00
7	21	21	0.00
8	9	9	0.00

Table 3.172: *Results of benchmark 3-15d, Initial vertical stress q_k for sand well compacted*

Vertical nr.	**Benchmark**	**D-GEO PIPELINE**	**Relative error**
[-]	[kN/m^2]	[kN/m^2]	[%]
1	1	1	0.00
2	5	5	0.00
3	99	99	0.00
4	127	127	0.00
5	95	95	0.00
6	36	36	0.00
7	14	14	0.00
8	8	8	0.00

Table 3.173: *Results of benchmark 3-15e, Initial vertical stress q_k for stiff clay well compacted*

Vertical nr.	**Benchmark**	**D-GEO PIPELINE**	**Relative error**
[-]	[kN/m^2]	[kN/m^2]	[%]
1	1	1	0.00
2	6	6	0.00
3	99	99	0.00
4	127	127	0.00
5	95	95	0.00
6	70	70	0.00
7	16	16	0.00
8	8	8	0.00

Table 3.174: *Results of benchmark 3-15f, Initial vertical stress q_k for soft soil well compacted*

Vertical nr.	**Benchmark**	**D-GEO PIPELINE**	**Relative error**
[-]	[kN/m^2]	[kN/m^2]	[%]
1	1	1	0.00
2	7	7	0.00
3	99	99	0.00
4	127	127	0.00
5	95	95	0.00
6	70	70	0.00
7	17	17	0.00
8	8	8	0.00

Table 3.175: *Results of benchmark 3-15a, Horizontal modulus of subgrade reaction and bearing capacities*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
	k_{h}	$P_{v;e}$	$P_{h;e}$	k_{h}	$P_{v;e}$	$P_{h;e}$	k_{h}	$P_{v;e}$	$P_{h;e}$
	[kN/m^3]	[kN/m^2]	[kN/m^2]	[kN/m^3]	[kN/m^2]	[kN/m^2]	[%]	[%]	[%]
v1	2970	64	36	2970	64	36	0.00	0.00	0.00
v2	3699	261	59	3699	261	59	0.00	0.00	0.00
v3	15130	1622	448	15130	1622	448	0.00	0.00	0.00
v4	16398	1433	416	16407	1433	416	0.05	0.00	0.00
v5	10278	733	234	10301	733	234	0.22	0.00	0.00
v6	767	615	15	774	615	16	0.9	0.00	6.25
v7	1212	52	23	1217	52	23	0.41	0.00	0.00
v8	4105	363	53	4095	363	53	0.24	0.00	0.00

Table 3.176: *Results of benchmark 3-15a, Vertical moduli of subgrade reaction upward*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
	$k_{v;top1}$	$k_{v;top2}$	$k_{v;top1}$	$k_{v;top2}$	$k_{v;top1}$	$k_{v;top2}$
	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[%]	[%]
v1	1	6	1	6	0.00	0.00
v2	37	85	37	85	0.00	0.00
v3	158782	231275	158781	231274	0.00	0.00
v4	734587	945256	735567	946483	0.13	0.13
v5	129440	172065	129743	172460	0.23	0.23
v6	3080	4265	3084	4270	0.13	0.12
v7	76	170	76	170	0.00	0.00
v8	12	57	12	57	0.00	0.00

Table 3.177: *Results of benchmark 3-15a, Vertical moduli of subgrade reaction downward*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
	$k_{v;bot1}$	$k_{v;bot2}$	$k_{v;bot1}$	$k_{v;bot2}$	$k_{v;bot1}$	$k_{v;bot2}$
	[kN/m^3]	[kN/m^3]	[kN/m^3]	[kN/m^3]	[%]	[%]
v1	1621	324	1621	324	0.00	0.00
v2	7876	1575	7876	1575	0.00	0.00
v3	39240	7848	39240	7848	0.00	0.00
v4	55098	11020	55116	11023	0.03	0.03
v5	31184	6237	31186	6237	0.01	0.00
v6	29860	5972	29863	5973	0.01	0.02
v7	812	162	813	163	0.12	0.61
v8	3695	591	3692	591	0.08	0.00

Table 3.178: *Results of benchmark 3-15a, Maximal axial friction and displacements*

	Benchmark			**D-GEO PIPELINE**			**Relative error**		
	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}	t_{max}	dv	d_{max}
	[kN/m^2]	[mm]	[mm]	[kN/m^2]	[mm]	[mm]	[%]	[%]	[%]
v1	19.76	5	12	24	5	12	16.67	0.00	0.00
v2	7.09	10	15	7	10	15	0.00	0.00	0.00
v3	12.59	20	2	13	20	2	0.00	0.00	0.00
v4	11.03	40	2	11	40	2	0.00	0.00	0.00
v5	9.6	80	5	10	80	5	0.00	0.00	0.00
v6	11.11	60	15	11	60	15	0.00	0.00	0.00
v7	14.05	50	15	14	50	15	0.00	0.00	0.00
v8	25.53	35	12	26	35	12	0.00	0.00	0.00

Table 3.179: *Results of benchmark 3-15a, Uplift check*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Vertical	f_{calc}	f_{req}	f_{calc}	f_{req}	f_{calc}	f_{req}
[-]	[-]	[-]	[-]	[-]	[%]	[%]
1	2.14	1.15	2.14	1.15	0.00	0.00
2	3.18	1.15	3.18	1.15	0.00	0.00
3	9.77	1.15	9.77	1.15	0.00	0.00
4	14.09	1.15	14.1	1.15	0.07	0.00
5	12.04	1.15	12.04	1.15	0.00	0.00
6	10.34	1.15	10.34	1.15	0.00	0.00
7	4.38	1.15	4.38	1.15	0.00	0.00
8	999	1.15	999	1.15	0.00	0.00

Table 3.180: *Results of benchmark 3-15a, Hydraulic heave check*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Vertical	f_{calc}	f_{req}	f_{calc}	f_{req}	f_{calc}	f_{req}
[-]	[-]	[-]	[-]	[-]	[%]	[%]
1	1.89	1.2	1.89	1.2	0.00	0.00
2	1.68	1.2	1.68	1.2	0.00	0.00
3	100	1.2	100	1.2	0.00	0.00
4	100	1.2	100	1.2	0.00	0.00
5	1.11	1.2	1.11	1.2	0.00	0.00
6	1.36	1.2	1.36	1.2	0.00	0.00
7	1.58	1.2	1.58	1.2	0.00	0.00
8	1.89	1.2	1.89	1.2	0.00	0.00

Use D-GEO PIPELINE input files bm3-15a.dri until bm3-15f to run this benchmark.

3.16 Trenching (3 sections) – 3D geometry in four layers – Drainage border above compressible border

3.16.1 Description

The same input values as benchmark 3-15 (section 3.15) are used, only the positions of the boundaries between compressible/incompressible layers and drained/undrained layers have

been turned around. This modification will only have an influence on the hydraulic heave check.

3.16.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Operation Parameters

The safety factors for hydraulic heave are determined using the formulas given in chapter "Trench" in the Background section of the User Manual of D-GEO PIPELINE. Intermediate results are given in the table below.

Table 3.181: *Analytical results for the hydraulic heave check*

	a	b	$d_{2;d}$	f_{Bous}	σ_v	σ_{bot}	W_{bot}	W_{top}	W_w	u_{opw}	φ	f
	[m]	[m]	[m]	[-]	[kN/m^2]						[m]	[-]
v1	2.6	0.28	0.48	0.04	24.3	16.6	7.7	16.6	10.2	16.5	-0.4	1.1
v2	4	0.28	-0.21	0	24.3	28.2	-3.9	28.2	17.1	16.5	-0.4	100
v3	8.7	0.28	-2.27	-0.13	27.8	71.9	-44	71.9	38.5	16.8	-0.4	100
v4	12.1	0.2	-1.77	-0.08	30.7	64.7	-34.1	64.7	34.1	17.1	-0.4	100
v5	10.8	0.2	-1.01	-0.04	34.9	54.1	-19.2	54.1	27.4	17.6	-0.5	100
v6	9.4	0.2	-0.25	0	39.1	44	-4.8	44	20.7	18	-0.5	100
v7	10.2	0.35	0.64	0.02	43.4	33.1	10.3	33.1	12.7	18.6	-0.6	1.3
v8	6.1	0.35	1.98	0.15	47.6	16.7	30.9	16.7	0.2	19.1	-0.6	1.8

3.16.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.182: *Results of benchmark 3-16, Hydraulic heave check*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Vertical	f_{calc}	f_{req}	f_{calc}	f_{req}	f_{calc}	f_{req}
[-]	[-]	[-]	[-]	[-]	[%]	[%]
1	1.13	1.2	1.13	1.2	0.00	0.00
2	100	1.2	100	1.2	0.00	0.00
3	100	1.2	100	1.2	0.00	0.00
4	100	1.2	100	1.2	0.00	0.00
5	100	1.2	100	1.2	0.00	0.00
6	100	1.2	100	1.2	0.00	0.00
7	1.27	1.2	1.26	1.2	0.79	0.00
8	1.76	1.2	1.75	1.2	0.57	0.00

Use D-GEO PIPELINE input file bm3-16.dri to run this benchmark.

3.17 Bundled pipeline with Special Stress Analysis

3.17.1 Description

The same input data's as for benchmark 3-9 (section 3.9) are used except that calculations are performed using the *Special Stress Analysis* calculation which means that the maximum modulus of subgrade reaction and the maximum reduced soil load are input values instead of calculated values: $k_{V;max}$ = 45000 kN/m^3, $q_{n;max}$ = 0.14 N/mm^2 and R = 700 m.

3.17.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Strength calculation for bundled pipelines

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter "Strength pipeline calculation" in the Background section of the User Manual of D-GEO PIPELINE. The properties of the equivalent pipe are:

$D_{0;eq}$	[mm]	1284.11
$d_{n;eq}$	[mm]	41.16
γ_{eq}	[kN/m^3]	58.92
I_{eq}	[m^4]	0.031073
E_{eq}	[N/mm^2]	74520.87
$k_{V;max;eq}$	[kN/m^3]	45000

The total pulling force is the contribution of five components. Results are given in the tables below for the equivalent pipeline and for each single pipelines.

Table 3.183: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-17) for the equivalent pipe*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	3887.97	0	0	0	0	3887.97
2	43.04	3794.48	103.16	0	0	0	3897.64
3	338	3153.74	0	707.01	395.49	296.1	4655.49
4	403.91	3010.56	157.99	0	0	0	4670.3
5	648.25	2479.76	0	1320.17	565.97	0	6025.65
6	769.54	2216.29	290.72	0	0	0	6052.89
7	1293.14	1078.88	0	1769.18	1028.93	0	7713.58
8	1440.63	758.48	353.53	0	0	0	7746.72
9	1715.52	161.33	0	658.9	489.65	427.18	8725.31
10	1789.79	0	178.02	0	0	0	8742

Table 3.184: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-17) for pipe nr. 1*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	2.6	0	0	0	0	2.6
2	43.04	2.54	2.6	0	0	0	5.14
3	338	2.11	0	17.83	0	1.53	24.08
4	403.91	2.02	3.98	0	0	0	27.97
5	648.25	1.66	0	14.77	3.66	0	46.05
6	769.54	1.48	7.33	0	0	0	53.2
7	1293.14	0.72	0	31.65	10.66	0	94.76
8	1440.63	0.51	8.92	0	0	0	103.46
9	1715.52	0.11	0	16.62	0	8.25	127.93
10	1789.79	0	4.49	0	0	0	132.31

Table 3.185: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-17) for pipe nr. 2*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	430.7	0	0	0	0	430.7
2	43.04	420.34	19.57	0	0	0	439.92
3	338	349.36	0	134.16	5.47	34.54	543.11
4	403.91	333.5	29.98	0	0	0	557.23
5	648.25	274.7	0	121.3	61.84	0	681.57
6	769.54	245.52	55.16	0	0	0	707.55
7	1293.14	119.52	0	245.27	119.69	0	946.51
8	1440.63	84.02	67.08	0	0	0	978.1
9	1715.52	17.87	0	125.03	6.78	66.17	1109.92
10	1789.79	0	33.78	0	0	0	1125.83

Table 3.186: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-17) for pipe nr. 3*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	164.16	0	0	0	0	164.16
2	43.04	160.21	27.49	0	0	0	187.7
3	338	133.16	0	188.42	0.36	23.73	373.16
4	403.91	127.11	42.1	0	0	0	409.21
5	648.25	104.7	0	156.75	49.67	0	593.22
6	769.54	93.58	77.47	0	0	0	659.57
7	1293.14	45.55	0	334.93	124.74	0	1071.21
8	1440.63	32.03	94.21	0	0	0	1151.9
9	1715.52	6.81	0	175.59	0.44	88.28	1391
10	1789.79	0	47.44	0	0	0	1431.63

Table 3.187: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-17) for pipe nr. 4*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	456.95	0	0	0	0	456.95
2	43.04	445.96	32.68	0	0	0	478.64
3	338	370.66	0	223.95	21.9	44.09	693.27
4	403.91	353.83	50.04	0	0	0	726.49
5	648.25	291.44	0	226.19	86.34	0	976.64
6	769.54	260.48	92.09	0	0	0	1037.76
7	1293.14	126.8	0	426.01	186.06	0	1516.16
8	1440.63	89.14	111.98	0	0	0	1590.48
9	1715.52	18.96	0	208.71	27.12	110.78	1866.91
10	1789.79	0	56.39	0	0	0	1904.33

Table 3.188: *Analytical results for the calculation of the five components of the pulling force for the 10 characteristic points (bm3-17) for pipe nr. 5*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	2833.56	0	0	0	0	2833.56
2	43.04	2765.42	76.94	0	0	0	2842.36
3	338	2298.45	0	527.34	361.45	221.71	3485.89
4	403.91	2194.1	117.84	0	0	0	3499.38
5	648.25	1807.25	0	1108.12	437.14	0	4657.8
6	769.54	1615.24	216.84	0	0	0	4682.62
7	1293.14	786.29	0	1405.99	808.45	0	6068.11
8	1440.63	552.78	263.69	0	0	0	6098.3
9	1715.52	117.58	0	491.46	447.51	330.13	6932.19
10	1789.79	0	132.78	0	0	0	6947.39

3.17.3 D-GEO PIPELINE results

A *Special Stress Analysis* calculation must be performed by selecting *Special Stress Analysis* for the *Start* menu. D-GEO PIPELINE results can be found in the *Report*.

Table 3.189: *Results of benchmark 3-17, Buoyancy Control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	1414	1415	0.07
Weight of pipeline (incl. filling)	[kg/m]	1086	1086	0.00
Effective weight of pipe	[kg/m]	328	328	0.00

Table 3.190: *Results of benchmark 3-17, Pulling forces in the pipeline*

	Benchmark		D-GEO PIPELINE		Relative error	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	3887.97	0	3887.97	0.00	0.00
T2	43.04	3897.64	43.04	3897.64	0.00	0.00
T3	338	4655.49	338	4655.49	0.00	0.00
T4	1440.63	7746.72	1440.63	7746.72	0.00	0.00
T5	1715.52	8725.31	1715.52	8725.31	0.00	0.00
T6	1789.79	8742	1789.79	8742	0.00	0.00
Max. rep. pulling force	-	4	-	4	-	0.00

Use D-GEO PIPELINE input file bm3-17.dri to run this benchmark.

3.18 HDD with 3D geometry – Pipeline configuration not ending at surface and with an angle between radii

3.18.1 Description

The same input values as benchmark 3-1 (section 3.1) are used, only the pipeline configuration is slightly different: the configuration is not ending at surface but 5 meters below the surface and an angle between the radii is present. Two cases are checked:

- ◇ Case A (bm3-18a): the angle between the radii is positive;
- ◇ Case B (bm3-18b): the angle between the radii is negative.

The configuration of the pipeline is given by:

X_{left}	10 m	X-coordinate of the left entry point
Y_{left}	10 m	Y-coordinate of the left entry point
Z_{left}	0 m	Z-coordinate of the left entry point
X_{right}	690 m	X-coordinate of the right exit point
Y_{right}	-30 m	Y-coordinate of the right exit point
Z_{right}	-5 m	Z-coordinate of the right exit point
φ_{left}	13°	Left angle of the pipe
φ_{right}	15°	Right angle of the pipe
Z_{bottom}	-50 m	Lowest level of the pipe
α	$\pm$2°	Angle of pipe between radii
R_{left}	600 m	Bending radius of the pipe at the left side
R_{right}	800 m	Bending radius of the pipe at the right side
R_{rol}	1000 m	Bending radius in pipe string (on rollers)

3.18.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Strength calculation

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter “Strength pipeline calculation” in the Background section of the User Manual of D-GEO PIPELINE. The position of the six characteristic points of the pipeline configuration is represented in Figure 3.5 and Figure 3.6. Their coordinates are given in the tables below.

Table 3.191: *Position of the 6 characteristic points (bm3-18a) for case a (positive angle between radii)*

Point	L-coord.	X-coord.	Z-coord.	Traject length
	[m]	[m]	[m]	[m]
1	10	10	0	0
2	161.55	161.29	-34.99	155.534
3	317.46	316.93	-50	312.614
4	350.59	350	-48.84	345.764
5	441.52	440.78	-45.67	436.752
6	620.66	619.6	-18.9	618.266

Table 3.192: *Position of the 6 characteristic points (bm3-18b) for case b*

Point	L-coord.	X-coord.	Z-coord.	Traject length
	[m]	[m]	[m]	[m]
1	10	10	0	0
2	144.81	144.57	-31.12	138.353
3	258.84	258.41	-46.14	253.545
4	350.59	350	-49.34	345.35
5	369.51	368.89	-50	364.287
6	604.49	603.46	-23.23	601.652

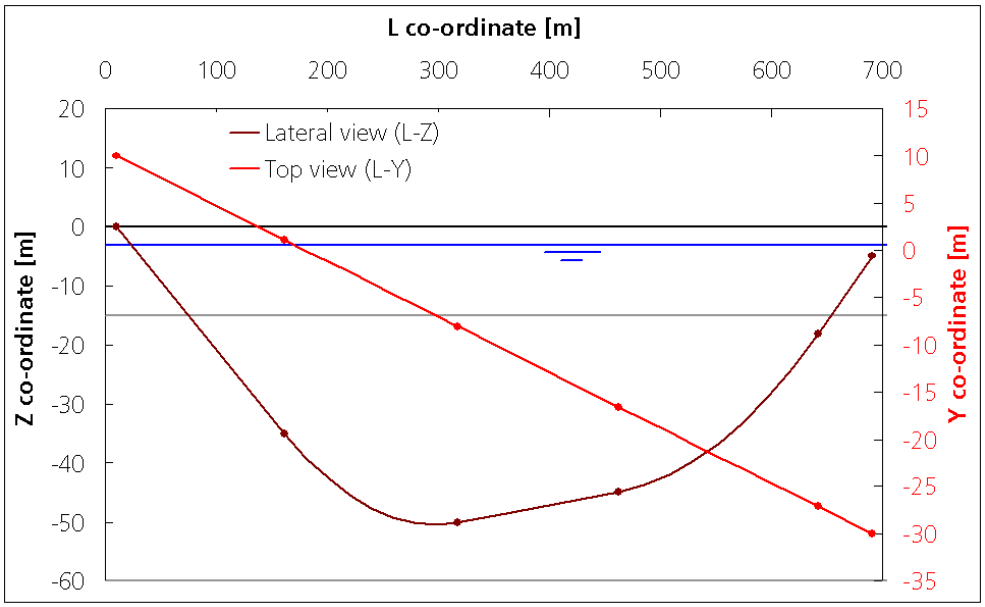

Figure 3.5: *Locations of the characteristic points T1 to T6 for case A (positive angle between radii)*

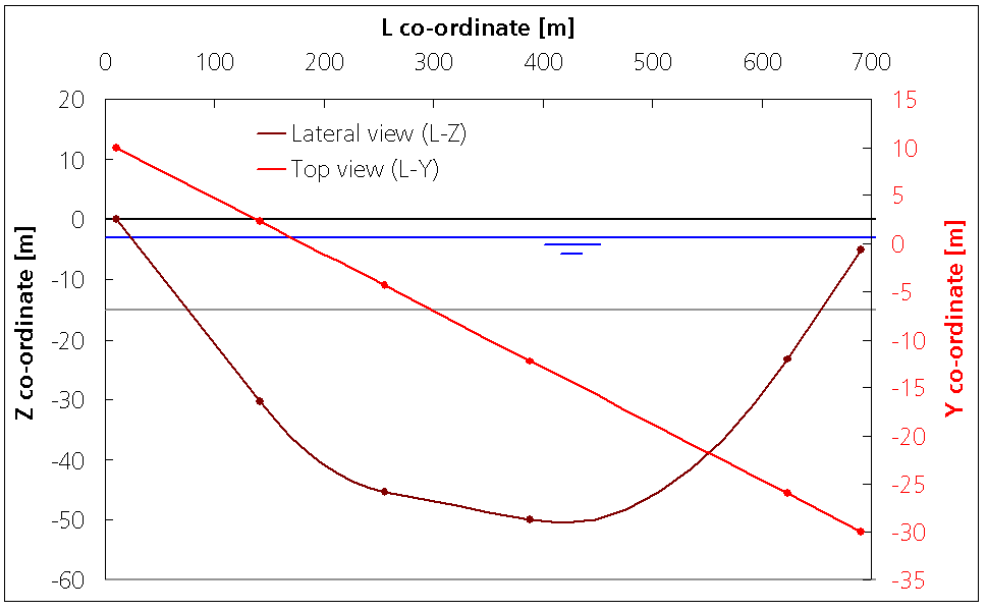

Figure 3.6: *Locations of the characteristic points T1 to T6 for case B (negative angle between radii)*

3.18.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the Dumpfile.

Table 3.193: *Results of benchmark 3-18a, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	284.5	0	284.5	0.00	0.00
T2	155.53	284.01	155.53	284.01	0.00	0.00
T3	312.61	471.53	312.61	471.53	0.00	0.00
T4	436.75	471.14	436.75	471.14	0.00	0.00
T5	618.27	620.94	618.27	620.94	0.00	0.00
T6	691.27	620.71	691.27	620.71	0.00	0.00
Max. rep. pulling force	-	5188	-	5188	-	0.00

Table 3.194: *Results of benchmark 3-18b, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	284.55	0	284.55	0.00	0.00
T2	138.35	284.11	138.35	284.11	0.00	0.00
T3	253.54	465.66	253.55	465.66	0.00	0.00
T4	364.29	465.31	364.29	465.31	0.00	0.00
T5	601.65	622.87	601.65	622.87	0.00	0.00
T6	691.4	622.58	691.4	622.59	0.00	0.00
Max. rep. pulling force	-	5187	-	5187	-	0.00

Use D-GEO PIPELINE input files bm3-18a.dri and bm3-18b.dri to run this benchmark.

3.19 HDD with 2D geometry – Stress Analysis per Vertical – Steel pipe

3.19.1 Description

The same sub-soil as benchmark 3-7 (section 3.7) is used, with a simple pipeline configuration as shown in Figure 3-7. A stress analysis per vertical is performed using 3 verticals at L = 70 m, L = 200 m and L = 1600 m.

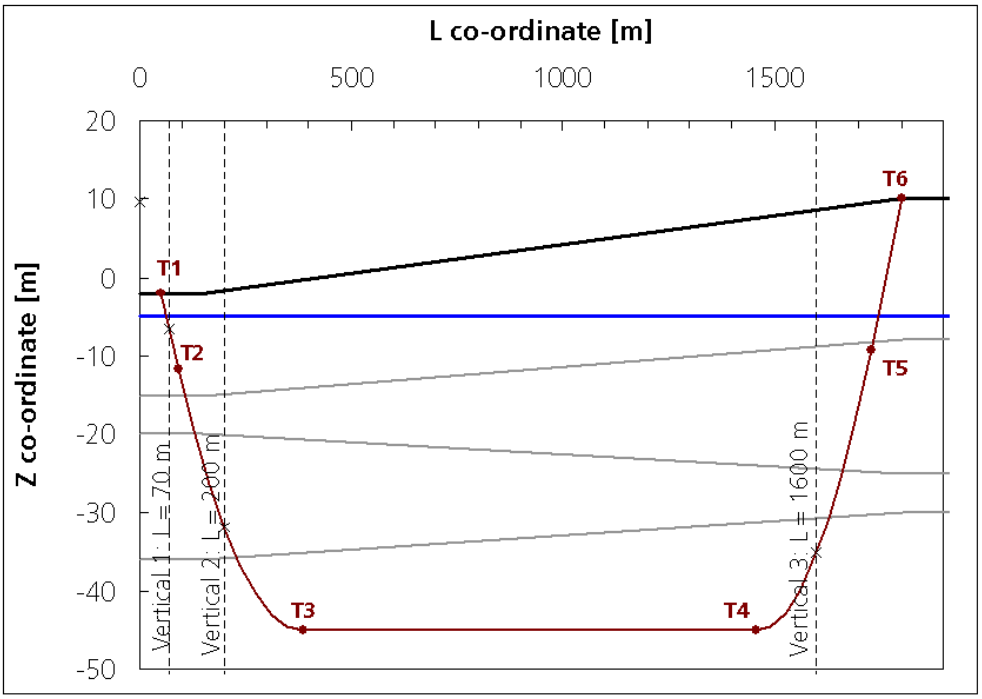

Figure 3.7: *Locations of the characteristic points (T1 to T6) and the 3 verticals*

3.19.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Soil mechanical data

The soil mechanical data's are determined using the formulas given in chapter "Calculation of soil mechanical data" in the Background section of the User Manual of D-GEO PIPELINE.

Strength calculation

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter "Strength pipeline calculation" in the Background section of the User Manual of D-GEO PIPELINE. For the radius, the following values are used for each vertical:

- ◇ Vertical 1, situated in the first (left) descending straight part: R = 100 000 000 m;
- ◇ Vertical 2, situated in the left curved part: R = 1300 m;
- ◇ Vertical 3, situated in the right curved part: R = 1050 m.

3.19.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.195: *Results of benchmark 3-19, Buoyancy Control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	2297	2297	0.00
Weight of pipeline (incl. filling)	[kg/m]	1288	1288	0.00
Effective weight of pipe	[kg/m]	1009	1009	0.00

Table 3.196: *Results of benchmark 3-19, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	4532	0	4532	0.00	0.00
T2	43	4622	43	4622	0.00	0.00
T3	338	6477	338	6477	0.00	0.00
T4	1410	8730	1410	8730	0.00	0.00
T5	1685	11136	1685	11136	0.00	0.00
T6	1759	11292	1759	11292	0.00	0.00
Max. rep. pulling force	-	36460	-	36460	-	0.00

Table 3.197: *Results of benchmark 3-19 for vertical nr. 1, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	304	304	0.00
σ_t	[N/mm^2]	49	49	0.00
$\sigma_{a;max}$	[N/mm^2]	353	353	0.00
$\sigma_{V;max}$	[N/mm^2]	353	353	0.00

Table 3.198: *Results of benchmark 3-19 for vertical nr. 1, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0	0	0.00
σ_t	[N/mm^2]	123	123	0.00
$\sigma_{a;max}$	[N/mm^2]	123	123	0.00
λ	[mm^{-1}]	0.000065	0.000065	0.00
q_r	[N/mm^2]	0	0	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
$\sigma_{t;max}$	[N/mm^2]	0	0	0.00
$\sigma_{V;max}$	[N/mm^2]	123	123	0.00

Table 3.199: *Results of benchmark 3-19 for vertical nr. 1, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	15	15	0.00
σ_{px}	[N/mm^2]	8	8	0.00
σ_{ptest}	[N/mm^2]	23	23	0.00
σ_{pm}	[N/mm^2]	13	13	0.00

Table 3.200: *Results of benchmark 3-19 for vertical nr. 1, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	0	0	0.00
$\sigma_{a;max}$	[N/mm^2]	0	0	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
σ_{qn}	[N/mm^2]	0	0	0.00
$\sigma_{t;max}$	[N/mm^2]	0	0	0.00
$\sigma_{V;max}$	[N/mm^2]	0	0	0.00

Table 3.201: *Results of benchmark 3-19 for vertical nr. 1, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	0	0	0.00
σ_{py}	[N/mm^2]	18	18	0.00
σ_{px}	[N/mm^2]	9	9	0.00
σ_{ptest}	[N/mm^2]	23	23	0.00
σ_{ptemp}	[N/mm^2]	25	25	0.00
$\sigma_{a;max}$	[N/mm^2]	9	9	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
σ_{qn}	[N/mm^2]	0	0	0.00
$\sigma_{V;max}$	[N/mm^2]	16	16	0.00

Table 3.202: *Results of benchmark 3-19 for vertical nr. 1, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	173.91	173.91	0.00
σ_{py}	[N/mm^2]	153.85	153.85	0.00
σ_{pm}	[N/mm^2]	169.23	169.23	0.00
$\sigma_{V;max}$	[N/mm^2]	261.54	261.54	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.203: *Results of benchmark 3-19 for vertical nr. 1, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	0	0	0.00
Max. allowable	[mm]	255	255	0.00
Max. allow. (piggability)	[mm]	120	120	0.00

Table 3.204: *Results of benchmark 3-19 for vertical nr. 1, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Table 3.205: *Results of benchmark 3-19 for vertical nr. 2, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	304	304	0.00
σ_t	[N/mm^2]	49	49	0.00
$\sigma_{a;max}$	[N/mm^2]	353	353	0.00
$\sigma_{V;max}$	[N/mm^2]	353	353	0.00

Table 3.206: *Results of benchmark 3-19 for vertical nr. 2, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	187	187	0.00
σ_t	[N/mm^2]	123	123	0.00
$\sigma_{a;max}$	[N/mm^2]	309	309	0.00
λ	[mm^{-1}]	0.000174	0.000174	0.00
q_r	[N/mm^2]	0.05052	0.05052	0.00
σ_{qr}	[N/mm^2]	20	20	0.00
$\sigma_{t;max}$	[N/mm^2]	20	20	0.00
$\sigma_{V;max}$	[N/mm^2]	320	320	0.00

Table 3.207: *Results of benchmark 3-19 for vertical nr. 2, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	15	15	0.00
σ_{px}	[N/mm^2]	8	8	0.00
σ_{ptest}	[N/mm^2]	23	23	0.00
σ_{pm}	[N/mm^2]	13	13	0.00

Table 3.208: *Results of benchmark 3-19 for vertical nr. 2, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	187	187	0.00
$\sigma_{a;max}$	[N/mm^2]	187	187	0.00
σ_{qr}	[N/mm^2]	20	20	0.00
σ_{qn}	[N/mm^2]	65	65	0.00
$\sigma_{t;max}$	[N/mm^2]	85	85	0.00
$\sigma_{V;max}$	[N/mm^2]	241	241	0.00

Table 3.209: *Results of benchmark 3-19 for vertical nr. 2, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	187	187	0.00
σ_{py}	[N/mm^2]	18	18	0.00
σ_{px}	[N/mm^2]	9	9	0.00
σ_{ptest}	[N/mm^2]	23	23	0.00
σ_{ptemp}	[N/mm^2]	25	25	0.00
$\sigma_{a;max}$	[N/mm^2]	196	196	0.00
σ_{qr}	[N/mm^2]	20	20	0.00
σ_{qn}	[N/mm^2]	65	65	0.00
$\sigma_{V;max}$	[N/mm^2]	239	239	0.00

Table 3.210: *Results of benchmark 3-19 for vertical nr. 2, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	173.91	173.91	0.00
σ_{py}	[N/mm^2]	153.85	153.85	0.00
σ_{pm}	[N/mm^2]	169.23	169.23	0.00
$\sigma_{V;max}$	[N/mm^2]	261.54	261.54	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.211: *Results of benchmark 3-19 for vertical nr. 2, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	6.1	6.1	0.00
Max. allowable	[mm]	255	255	0.00
Max. allow. (piggability)	[mm]	120	120	0.00

Table 3.212: *Results of benchmark 3-19 for vertical nr. 2, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Table 3.213: *Results of benchmark 3-19 for vertical nr. 3, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	304	304	0.00
σ_t	[N/mm^2]	49	49	0.00
$\sigma_{a;max}$	[N/mm^2]	353	353	0.00
$\sigma_{V;max}$	[N/mm^2]	353	353	0.00

Table 3.214: *Results of benchmark 3-19 for vertical nr. 3, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	231	231	0.00
σ_t	[N/mm^2]	123	123	0.00
$\sigma_{a;max}$	[N/mm^2]	354	354	0.00
λ	[mm^{-1}]	0.000167	0.000167	0.00
q_r	[N/mm^2]	0.0578	0.0578	0.00
σ_{qr}	[N/mm^2]	23	23	0.00
$\sigma_{t;max}$	[N/mm^2]	23	23	0.00
$\sigma_{V;max}$	[N/mm^2]	366	366	0.00

Table 3.215: *Results of benchmark 3-19 for vertical nr. 3, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	15	15	0.00
σ_{px}	[N/mm^2]	8	8	0.00
σ_{ptest}	[N/mm^2]	23	23	0.00
σ_{pm}	[N/mm^2]	13	13	0.00

Table 3.216: *Results of benchmark 3-19 for vertical nr. 3, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	231	231	0.00
$\sigma_{a;max}$	[N/mm^2]	231	231	0.00
σ_{qr}	[N/mm^2]	23	23	0.00
σ_{qn}	[N/mm^2]	95	95	0.00
$\sigma_{t;max}$	[N/mm^2]	117	117	0.00
$\sigma_{V;max}$	[N/mm^2]	307	307	0.00

Table 3.217: *Results of benchmark 3-19 for vertical nr. 3, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	231	231	0.00
σ_{py}	[N/mm^2]	18	18	0.00
σ_{px}	[N/mm^2]	9	9	0.00
σ_{ptest}	[N/mm^2]	23	23	0.00
σ_{ptemp}	[N/mm^2]	25	25	0.00
$\sigma_{a;max}$	[N/mm^2]	240	240	0.00
σ_{qr}	[N/mm^2]	23	23	0.00
σ_{qn}	[N/mm^2]	95	95	0.00
$\sigma_{V;max}$	[N/mm^2]	304	304	0.00

Table 3.218: *Results of benchmark 3-19 for vertical nr. 3, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	173.91	173.91	0.00
σ_{py}	[N/mm^2]	153.85	153.85	0.00
σ_{pm}	[N/mm^2]	169.23	169.23	0.00
$\sigma_{V;max}$	[N/mm^2]	261.54	261.54	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.219: *Results of benchmark 3-19 for vertical nr. 3, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	8.2	8.2	0.00
Max. allowable	[mm]	255	255	0.00
Max. allow. (piggability)	[mm]	120	120	0.00

Table 3.220: *Results of benchmark 3-19 for vertical nr. 3, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Use D-GEO PIPELINE input file bm3-19.dri to run this benchmark.

3.20 HDD with 3D geometry – Stress Analysis per Vertical – PE pipe

3.20.1 Description

The same input as for benchmark 3-10 (section 3.10) is used except that a stress analysis per vertical instead of a standard analysis is performed using 3 verticals at L = 60 m, L = 170 m and L = 1000 m and only one synthetic pipe (PE 80) is used.

3.20.2 Analytical results

Analytical results are worked out in an Excel spreadsheet.

Strength calculation for bundled pipelines

For the buoyancy control, the pulling forces in the pipeline and the strength calculation, calculations are performed using the formulas given in chapter “Strength pipeline calculation” in the Background section of the User Manual of D-GEO PIPELINE. For the radius, the following values are used for each vertical:

- ◇ Vertical 1, situated in the first (left) descending straight part: R = 100 000 000 m;
- ◇ Vertical 2, situated in the left curved part: R = 1300 m;
- ◇ Vertical 3, situated in the second bending: R = 1000.008 m.

3.20.3 D-GEO PIPELINE results

D-GEO PIPELINE results presented in the tables below can be found in the *Report*.

Table 3.221: *Results of benchmark 3-20, Buoyancy Control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	653	654	0.15
Weight of pipeline (incl. filling)	[kg/m]	166	166	0.00
Effective weight of pipe	[kg/m]	488	488	0.00

Table 3.222: *Results of benchmark 3-20, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	582	0	582	0.00	0.00
T2	43	669	43	669	0.00	0.00
T3	338	1353	338	1353	0.00	0.00
T4	1410	3510	1410	3510	0.00	0.00
T5	1685	4387	1685	4387	0.00	0.00
T6	1759	4537	1759	4537	0.00	0.00
Max. rep. pulling force	-	897	-	897	-	0.00

Table 3.223: *Results of benchmark 3-20 for vertical nr. 1, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	1	1	0.00
σ_t	[N/mm^2]	6	6	0.00
$\sigma_{a;max}$	[N/mm^2]	6	6	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.224: *Results of benchmark 3-20 for vertical nr. 1, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0	0	0.00
σ_t	[N/mm^2]	45	45	0.00
$\sigma_{a;max}$	[N/mm^2]	45	45	0.00
λ	[mm^{-1}]	0.000398	0.000398	0.00
q_r	[N/mm^2]	0	0	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
$\sigma_{t;max}$	[N/mm^2]	0	0	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.225: *Results of benchmark 3-20 for vertical nr. 1, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	5	5	0.00
σ_{px}	[N/mm^2]	2	2	0.00
σ_{ptest}	[N/mm^2]	7	7	0.00
σ_{pm}	[N/mm^2]	4	4	0.00

Table 3.226: *Results of benchmark 3-20 for vertical nr. 1, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	0	0	0.00
$\sigma_{a;max}$	[N/mm^2]	0	0	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
σ_{qn}	[N/mm^2]	0	0	0.00
$\sigma_{t;max}$	[N/mm^2]	0	0	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.227: *Results of benchmark 3-20 for vertical nr. 1, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{b}	[N/mm^2]	0	0	0.00
σ_{py}	[N/mm^2]	5	5	0.00
σ_{px}	[N/mm^2]	2	2	0.00
σ_{ptest}	[N/mm^2]	7	7	0.00
σ_{ptemp}	[N/mm^2]	0	0	0.00
$\sigma_{a;max}$	[N/mm^2]	2	2	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
σ_{qn}	[N/mm^2]	0	0	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.228: *Results of benchmark 3-20 for vertical nr. 1, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	6.4	6.4	0.00
σ_{py}	[N/mm^2]	5.04	5.04	0.00
σ_{pm}	[N/mm^2]	n.a.	n.a.	
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (short)	[N/mm^2]	6.4	6.4	0.00
$\sigma_{a/t}$ (long)	[N/mm^2]	5.04	5.04	0.00

Table 3.229: *Results of benchmark 3-20 for vertical nr. 1, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	0	0	0.00
Max. allowable	[mm]	64	64	0.00
Max. allow. (piggability)	[mm]	44.8	44.8	0.00

Table 3.230: *Results of benchmark 3-20 for vertical nr. 1, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	297	297	0.00
Max. allow. external pressure (long)	[kPa]	30	30	0.00
Int. pressure due to 100% filling (short)	[kPa]	0	0	0.00
Int. pressure due to 100% filling (long)	[kPa]	0	0	0.00

Table 3.231: *Results of benchmark 3-20 for vertical nr. 2, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	1	1	0.00
σ_t	[N/mm^2]	6	6	0.00
$\sigma_{a;max}$	[N/mm^2]	6	6	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.232: *Results of benchmark 3-20 for vertical nr. 2, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0	0	0.00
σ_t	[N/mm^2]	45	45	0.00
$\sigma_{a;max}$	[N/mm^2]	45	45	0.00
λ	[mm^{-1}]	0.001125	0.001125	0.00
q_r	[N/mm^2]	0.00313	0.00313	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
$\sigma_{t;max}$	[N/mm^2]	0	0	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.233: *Results of benchmark 3-20 for vertical nr. 2, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	5	5	0.00
σ_{px}	[N/mm^2]	2	2	0.00
σ_{ptest}	[N/mm^2]	7	7	0.00
σ_{pm}	[N/mm^2]	4	4	0.00

Table 3.234: *Results of benchmark 3-20 for vertical nr. 2, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0	0	0.00
$\sigma_{a;max}$	[N/mm^2]	0	0	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
σ_{qn}	[N/mm^2]	4	4	0.00
$\sigma_{t;max}$	[N/mm^2]	3	3	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.235: *Results of benchmark 3-20 for vertical nr. 2, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0	0	0.00
σ_{py}	[N/mm^2]	5	5	0.00
σ_{px}	[N/mm^2]	2	2	0.00
σ_{ptest}	[N/mm^2]	7	7	0.00
σ_{ptemp}	[N/mm^2]	0	0	0.00
$\sigma_{a;max}$	[N/mm^2]	2	2	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
σ_{qn}	[N/mm^2]	4	4	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.236: *Results of benchmark 3-20 for vertical nr. 2, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	6.4	6.4	0.00
σ_{py}	[N/mm^2]	5.04	5.04	0.00
σ_{pm}	[N/mm^2]	n.a.	n.a.	
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (short)	[N/mm^2]	6.4	6.4	0.00
$\sigma_{a/t}$ (long)	[N/mm^2]	5.04	5.04	0.00

Table 3.237: *Results of benchmark 3-20 for vertical nr. 2, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	32.6	33	1.22699386503067
Max. allowable	[mm]	64	64	0.00
Max. allow. (piggability)	[mm]	44.8	44.8	0.00

Table 3.238: *Results of benchmark 3-20 for vertical nr. 2, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	297	297	0.00
Max. allow. external pressure (long)	[kPa]	30	30	0.00
Int. pressure due to 100% filling (short)	[kPa]	0	0	0.00
Int. pressure due to 100% filling (long)	[kPa]	0	0	0.00

Table 3.239: *Results of benchmark 3-20 for vertical nr. 3, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	1	1	0.00
σ_t	[N/mm^2]	6	6	0.00
$\sigma_{a;max}$	[N/mm^2]	6	6	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.240: *Results of benchmark 3-20 for vertical nr. 3, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	1	1	0.00
σ_t	[N/mm^2]	45	45	0.00
$\sigma_{a;max}$	[N/mm^2]	45	45	0.00
λ	[mm^{-1}]	0.000994	0.000994	0.00
q_r	[N/mm^2]	0.00302	0.00302	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
$\sigma_{t;max}$	[N/mm^2]	0	0	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.241: *Results of benchmark 3-20 for vertical nr. 3, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	5	5	0.00
σ_{px}	[N/mm^2]	2	2	0.00
σ_{ptest}	[N/mm^2]	7	7	0.00
σ_{pm}	[N/mm^2]	4	4	0.00

Table 3.242: *Results of benchmark 3-20 for vertical nr. 3, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0	0	0.00
$\sigma_{a;max}$	[N/mm^2]	0	0	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
σ_{qn}	[N/mm^2]	4	4	0.00
$\sigma_{t;max}$	[N/mm^2]	3	3	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.243: *Results of benchmark 3-20 for vertical nr. 3, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0	0	0.00
σ_{py}	[N/mm^2]	5	5	0.00
σ_{px}	[N/mm^2]	2	2	0.00
σ_{ptest}	[N/mm^2]	7	7	0.00
σ_{ptemp}	[N/mm^2]	0	0	0.00
$\sigma_{a;max}$	[N/mm^2]	2	2	0.00
σ_{qr}	[N/mm^2]	0	0	0.00
σ_{qn}	[N/mm^2]	4	4	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.244: *Results of benchmark 3-20 for vertical nr. 3, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	6.4	6.4	0.00
σ_{py}	[N/mm^2]	5.04	5.04	0.00
σ_{pm}	[N/mm^2]	n.a.	n.a.	
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (short)	[N/mm^2]	6.4	6.4	0.00
$\sigma_{a/t}$ (long)	[N/mm^2]	5.04	5.04	0.00

Table 3.245: *Results of benchmark 3-20 for vertical nr. 3, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	36.6	37	1.09289617486339
Max. allowable	[mm]	64	64	0.00
Max. allow. (piggability)	[mm]	44.8	44.8	0.00

Table 3.246: *Results of benchmark 3-20 for vertical nr. 3, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	297	297	0.00
Max. allow. external pressure (long)	[kPa]	30	30	0.00
Int. pressure due to 100% filling (short)	[kPa]	0	0	0.00
Int. pressure due to 100% filling (long)	[kPa]	0	0	0.00

Use D-GEO PIPELINE input file bm3-20.dri to run this benchmark.

3.21 HDD – Determination of the minimum allowable radius

3.21.1 Description

This benchmark checks the determination of the minimum allowable radius in two cases:

- ◇ Case A (bm3-21a): 4 different steel pipes with a diameter of 399, 400, 401 and 2000 mm are tested;
- ◇ Case B (bm3-21b): 20 different PE pipes with a diameter of 63, 100, 160, 180, 200, 225, 250, 290, 315, 335, 355, 380, 400, 500, 630, 680, 710, 760, 800 and 1000 mm are tested.

Case A

In case A, two bending radius are present: a radius of 1750 m at the left and 500 m at the right as shown in Figure 3.8.

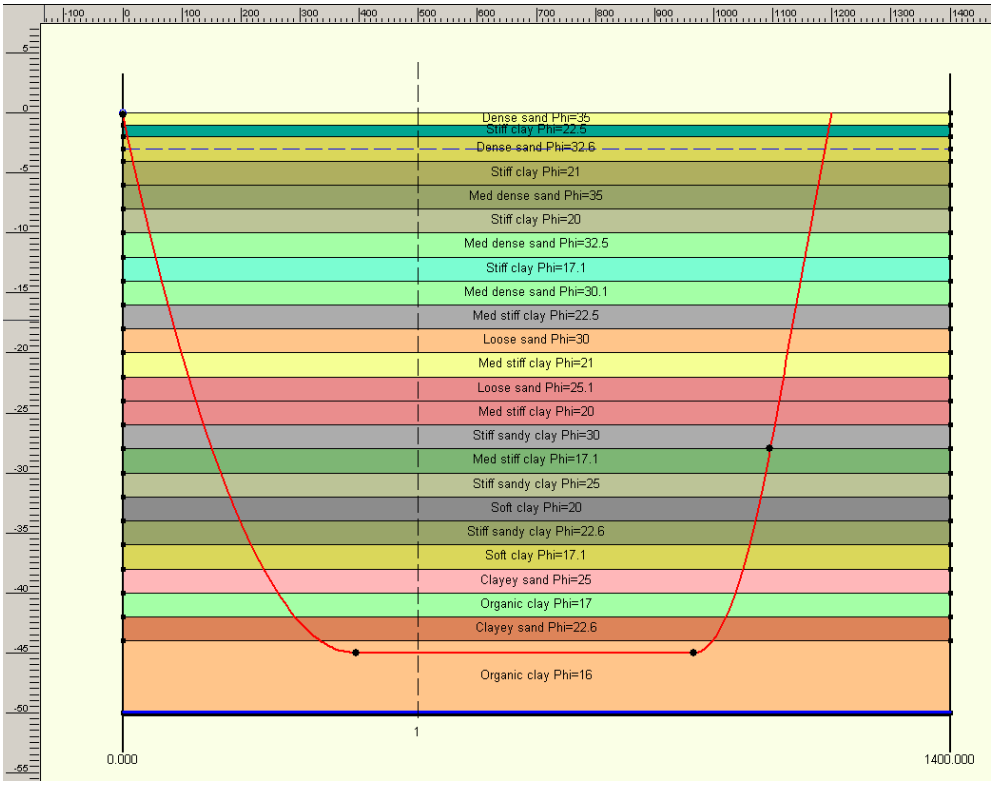

Figure 3.8: *Geometry of benchmark 3-21a*

The soil properties of the different are given in Table 3.247.

Table 3.247: *Properties of the different layers in benchmark 21a*

Name	**Soil type**	***c***	φ	**Top level**	**Constant *C***
		[kN/m^2]	[°]	[m]	[-]
Dense sand Phi 35	Dense sand	1	35	0	9400
Stiff clay Phi 22.5	Stiff clay	15	22.5	-1	10500
Dense sand Phi 32.6	Dense sand	0.5	32.6	-2	9400
Stiff clay Phi 21	Stiff clay	10.1	21	-4	10500
Med dense sand Phi 35	Med dense sand	0.6	35	-6	9400
Stiff clay Phi 20	Stiff clay	15	20	-8	10500
Med dense sand Phi 32.5	Med dense sand	2	32.5	-10	9400
Stiff clay Phi 17.1	Stiff clay	10.1	17.1	-12	10500
Med dense sand Phi 30.1	Med dense sand	0.6	30.1	-14	9400
Med stiff clay Phi 22.5	Med stiff clay	10	22.5	-16	11500
Loose sand Phi 30	Loose sand	1	30	-18	10500
Med stiff clay Phi 21	Med stiff clay	7	21	-20	11500
Loose sand Phi 25.1	Loose sand	0.1	25.1	-22	10500
Med stiff clay Phi 20	Med stiff clay	10	20	-24	11500
Stiff sandy clay Phi 30	Stiff sandy clay	1.1	30	-26	10500
Med stiff clay Phi 17.1	Med stiff clay	5.1	17.1	-28	11500
Stiff sandy clay Phi 25	Stiff sandy clay	5.1	25	-30	10500
Soft clay Phi 20	Soft clay	5	20	-32	12500
Stiff sandy clay Phi 22.6	Stiff sandy clay	12	22.6	-34	10500
Soft clay Phi 17.1	Soft clay	3	17.1	-36	12500
Clayey sand Phi 25	Clayey sand	5	25	-38	10500
Organic clay Phi 17	Organic clay	15	17	-40	12500
Clayey sand Phi 22.6	Clayey sand	4	22.6	-42	10500
Organic clay Phi 16	Organic clay	30	16	-44	12500

Case B

In case B, four bending radius are present as shown in Figure 3.9.

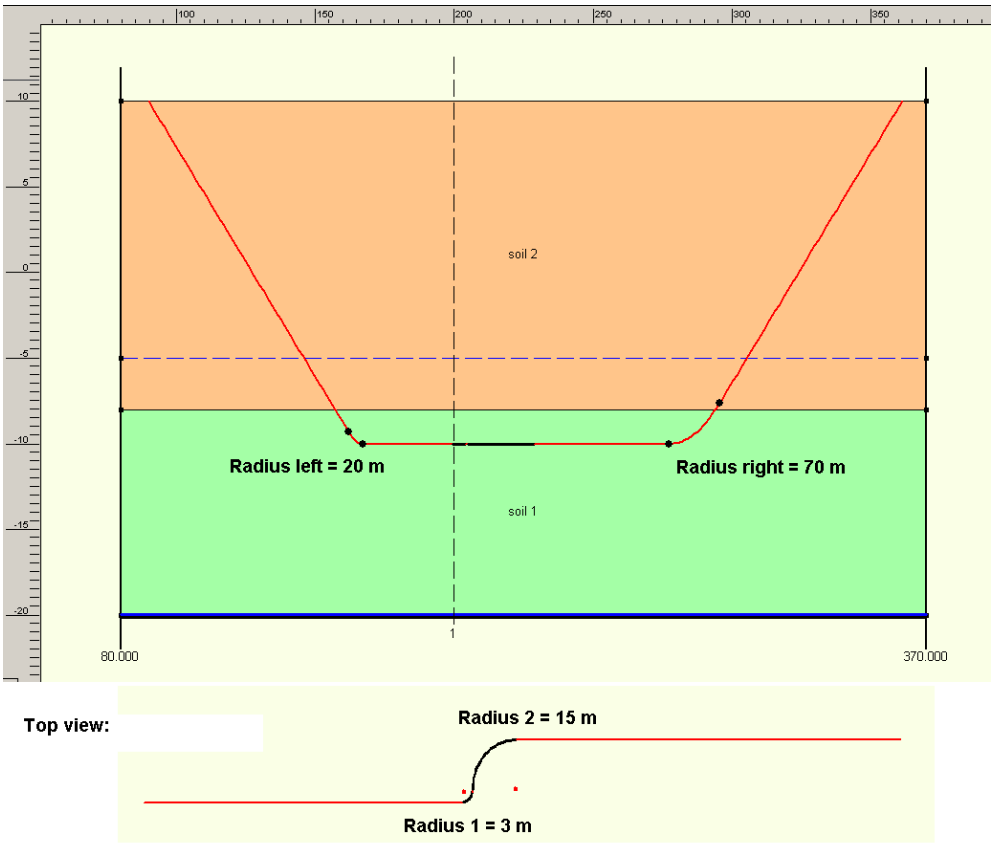

Figure 3.9: *Geometry of benchmark 3-21b*

3.21.2 Analytical results

Case A: Allowable curve radius for steel pipes

The minimum allowable radius for steel pipes is:

$R \geq 1000 \times D_0$ for small pipe diameter ($D_0 \leq 0.4$ m)

$R \geq C \times \sqrt{D_0 \times d_n}$ for large pipe diameter ($D_0 > 0.4$ m)

where *C* is a constant (without dimension) depending on the soil type as shown in Table 3.248.

Table 3.248: *Values of constant C (according to table E.1 of NEN 3650-1 (NEN, 2012a))*

Soil type	**Constant *C* [-]**
Dense packed sand	8500
Moderate packed sand	9400
Loose packed sand	10200
Stiff clay	10500
Medium stiff clay	11500
Soft clay and peat	12500

In D-GEO PIPELINE, the soil type is a function of the cohesion and the friction angle of the soil, as shown in Table 3.249.

Table 3.249: *Soil type as a function of the cohesion and the friction angle*

Soil type	φ [°]	c [kN/m^2]	**Constant *C* [-]**
Dense sand	$\varphi > 32.5$	$c \leq 0.5$	8500
Medium dense sand	$\varphi > 32.5$	$c > 0.5$	9400
Medium dense sand	$30 < \varphi \leq 32.5$		9400
Loose sand	$25 < \varphi \leq 30$	$c \leq 1$	10200
Stiff sandy clay	$25 < \varphi \leq 30$	$c > 1$	10500
Stiff sandy clay	$22.5 < \varphi \leq 25$	$c > 5$	10200
Clayey sand	$22.5 < \varphi \leq 25$	$c \leq 5$	10500
Stiff clay	$20 < \varphi \leq 22.5$	$c > 10$	10500
Medium stiff clay	$20 < \varphi \leq 22.5$	$c \leq 10$	11500
Stiff clay	$17 < \varphi \leq 20$	$c > 10$	10500
Medium stiff clay	$17 < \varphi \leq 20$	$5 < c \leq 10$	11500
Soft clay	$17 < \varphi \leq 20$	$c \leq 5$	12500
Peat /organic clay	$\varphi \leq 17$		12500

In the case of a layered sub-soil, the highest *C*-value of a layer with a significant thickness is normative. In the case of a sub-soil with an alternation of layers with relative small thicknesses, a weighted interpolation can be performed to determine the *C*-value:

$$C_{\text{d}} = \sum_{\text{i}=1}^{\text{n}} \left[C_{\text{i}} \times \frac{d_{\text{i}}}{d_{\text{total}}} \right] \quad \text{where} \quad d_{\text{total}} = \sum_{\text{i}=1}^{\text{n}} d_{\text{i}} \tag{3.7}$$

in which:

n	Total number of layers in the curve [-]
C_{i}	C-value of layer i [-]
d_{i}	Thickness of layer i [m]
d_{total}	Total thickness of all layers in the curve [m]

Case B: Allowable curve radius for polyethylene pipes

According to article 8.6.4 of NEN 3650-3 (NEN, 2012c), the minimal curve-radius for PE pipes is equal to the bending factor as given in Table 3.250 times the diameter.

Table 3.250: *Bending factor (acc. to table 6 of NEN 3650-3)*

Diameter in mm	**Bending factor**
$63 \rightarrow 160$	50
$200 \rightarrow 250$	75
$315 \rightarrow 355$	100
$400 \rightarrow 630$	100
$710 \rightarrow 800$	125

3.21.3 D-GEO PIPELINE results

The check for the minimum curve radius is performed in D-GEO PIPELINE by means of warning messages appearing when starting a calculation, as shown in Figure 3.10 and Figure 3.11.

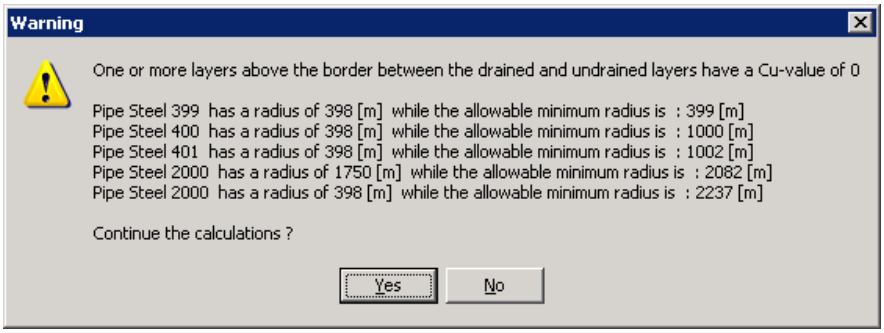

Figure 3.10: *Warning message displayed for benchmark 3-21a*

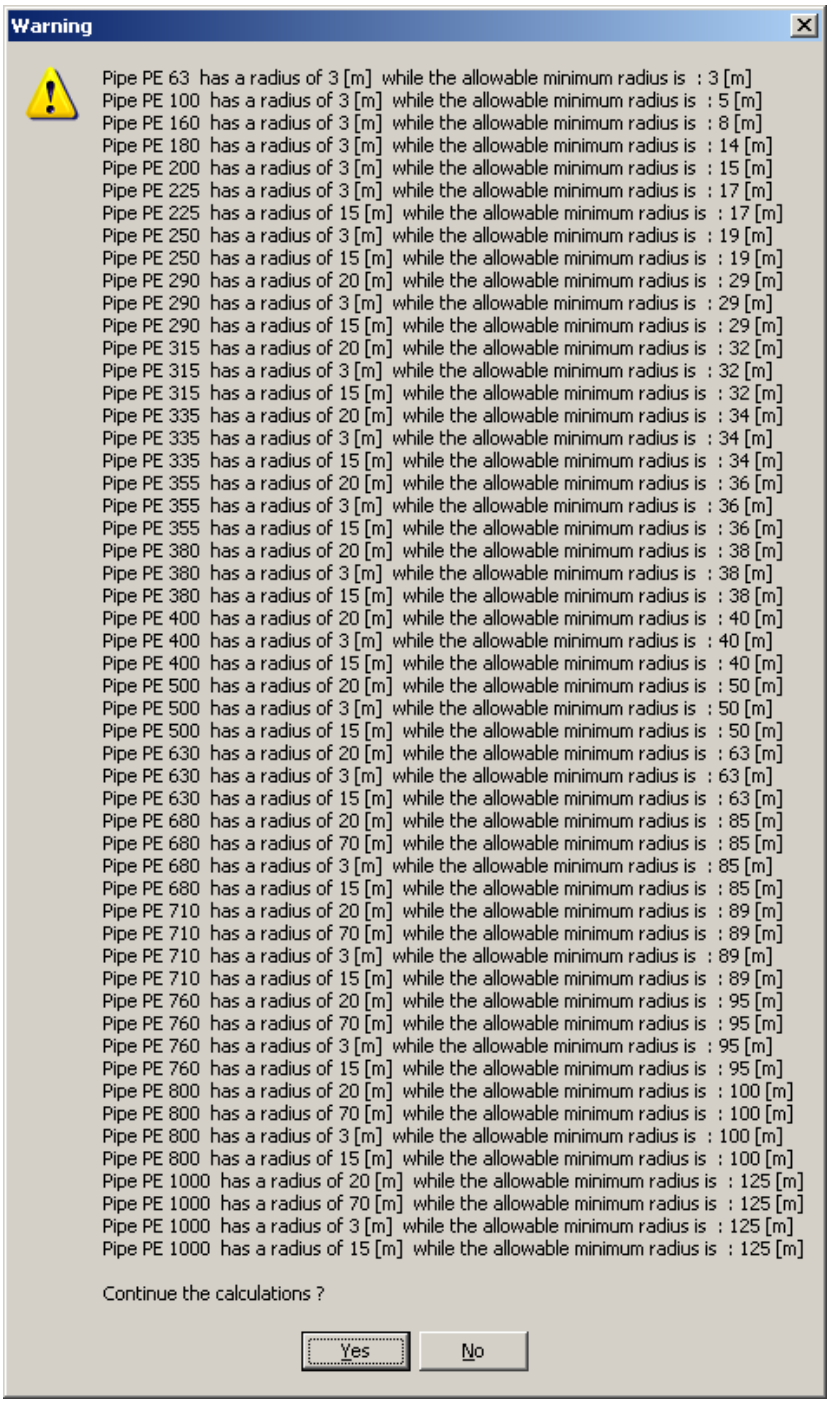

Figure 3.11: *Warning message displayed for benchmark 3-21b*

Table 3.251: *Results of benchmark 3-21a, Allowable minimum radius for steel pipes*

Pipe	**Benchmark**		**D-GEO PIPELINE**		**Error [%]**	
R [m] →	1750	398	1750	398	1750	398
	[m]	[m]	[m]	[m]	[%]	[%]
⊘ 399 mm	399	399		399		0
⊘ 400 mm	1631	2195		1000		119.5
⊘ 401 mm	1633	2197		1002		119.26
⊘ 2000 mm	3647	4907	2082	2237	75.17	119.36

Table 3.252: *Results of benchmark 3-21b, Allowable minimum radius for PE pipes*

	Benchmark				**D-GEO PIPELINE**				**Error [%]**			
R [m] →	3	15	20	70	3	15	20	70	3	15	20	70
	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[%]	[%]	[%]	[%]
⊘ 63 mm	3				3				0			
⊘ 100 mm	5				5				0			
⊘ 160 mm	8				8				0			
⊘ 180 mm	14				14				0			
⊘ 200 mm	15	15			15	15			0	0		
⊘ 225 mm	17	17			17	17			0	0		
⊘ 250 mm	19	19			19	19			0	0		
⊘ 290 mm	29	29	29		29	29	29		0	0	0	
⊘ 315 mm	32	32	32		32	32	32		0	0	0	
⊘ 335 mm	34	34	34		34	34	34		0	0	0	
⊘ 355 mm	36	36	36		36	36	36		0	0	0	
⊘ 380 mm	38	38	38		38	38	38		0	0	0	
⊘ 400 mm	40	40	40		40	40	40		0	0	0	
⊘ 500 mm	50	50	50		50	50	50		0	0	0	
⊘ 630 mm	63	63	63		63	63	63		0	0	0	
⊘ 680 mm	85	85	85	85	85	85	85	85	0	0	0	0
⊘ 710 mm	89	89	89	89	89	89	89	89	0	0	0	0
⊘ 760 mm	95	95	95	95	95	95	95	95	0	0	0	0
⊘ 800 mm	100	100	100	100	100	100	100	100	0	0	0	0
⊘ 1000 mm	125	125	125	125	125	125	125	125	0	0	0	0

Use D-GEO PIPELINE input files bm3-21a.dri and bm3-21b.dri to run this benchmark.

3.22 HDD – PE pipe not filled with water on rollers

3.22.1 Description

This benchmark checks the effect of not-filling the pipe on rollers with water. The same input data's as for benchmark 3-3 (section 3.3) are used except that the option *Pipe filled with water on rollers* is unchecked. This should have an influence on the calculation of T_1, the pulling force due to friction of the pipeline on the roller-lane.

3.22.2 Analytical results

The pulling force due to friction of the pipeline on the roller-lane is:

$$T_1 = f_1 \times L_{\text{rol}} \times g \tag{3.8}$$

where g = g_{pipe} = 1.069 N/mm is the weight of the pipe on roller, without water filling, whereas for benchmark 3-3 (pipe filled with water on rollers) this weight is equal to:
g = g_{pipe} + g_{fill} =1.069 + 0.391= 1.460 N/mm.
Analytical results are worked out in an Excel spreadsheet. Results are given in the table below.

Table 3.253: *Analytical results for the calculation of the five components of the pulling force for the six characteristic points*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	73.82	0	0	0	0	73.82
2	153.91	57.37	144.61	0	0	0	201.97
3	290.04	42.81	0	127.91	5.72	14.54	335.59
4	393.19	31.79	45.17	0	0	0	421.47
5	602.62	9.39	0	196.78	4.29	31.33	631.48
6	690.49	0	82.55	0	0	0	704.64

3.22.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.254: *Results of benchmark 3-22, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	73.82	0	73.82	0.00	0.00
T2	153.91	201.97	153.91	201.98	0.00	0.00
T3	290.04	335.59	290.05	335.59	0.00	0.00
T4	393.19	421.47	393.19	421.47	0.00	0.00
T5	602.62	631.48	602.63	631.48	0.00	0.00
T6	690.49	704.64	690.49	704.64	0.00	0.00
Max. rep. pulling force	-	829	-	829	-	0.00

Use D-GEO PIPELINE input file bm3-22.dri to run this benchmark.

3.23 HDD – PE pipe always filled (100%) – Implosion

3.23.1 Description

This benchmark checks the effect of completely filling the pipe with fluid during pull back. The same input data's as for benchmark 3-3 (section 3.3) are used except that the part of the pipe filled with fluid during pull back is 100% instead of 10%. This should have an influence on the calculation of the effective weight of the pipe (and the the pulling forces) and on the internal pressure during implosion check.

3.23.2 Analytical results

The weight of the filling with fluid is equal to:
g_{fill} = 100% $\times \gamma_{\text{w}} \times A_{\text{inw}}$ = 3.906 N/mm
whereas for benchmark 3-3 (pipe filled with 10% fluid) this weight is equal to:
g_{fill} = 0.3906 N/mm.
This will therefore have an infuence on the pulling forces. Analytical results are worked out in an Excel spreadsheet. Results are given in Table 3.255.

Table 3.255: *Analytical results for the calculation of the five components of the pulling force for the six characteristic points*

Charac. point	Length [m]	T_1 [kN]	T_2 [kN]	T_{3a} [kN]	T_{3b} [kN]	T_{3c} [kN]	Total [kN]
1	0	343.52	0	0	0	0	343.52
2	153.91	266.95	36.4	0	0	0	303.35
3	290.04	199.22	0	32.2	5.72	12.39	285.93
4	393.19	147.91	11.37	0	0	0	259.01
5	602.62	43.71	0	49.53	4.29	10.89	219.53
6	690.49	0	20.78	0	0	0	196.6

During implosion check, the internal pressure due to complete filling is not nil but equal to:

$$P_{\text{filling}} = \gamma_{\text{fluid}} \times [\min(Z_{\text{left}}; Z_{\text{right}}) - Z_{\text{bottom}}] \tag{3.9}$$

This leads to: P_{filling} = 12 $\times$ (0 + 50) = 600 kN/m^2.

3.23.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.256: *Results of benchmark 3-23, Buoyancy Control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	553	553	0.00
Weight of pipeline (incl. filling)	[kg/m]	497	498	0.20
Effective weight of pipe	[kg/m]	55	55	0.00

Table 3.257: *Results of benchmark 3-23, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	343.52	0	343.52	0.00	0.00
T2	153.91	303.35	153.91	303.35	0.00	0.00
T3	290.04	285.93	290.05	285.93	0.00	0.00
T4	393.19	259.01	393.19	259.01	0.00	0.00
T5	602.62	219.53	602.63	219.53	0.00	0.00
T6	690.49	196.6	690.49	196.6	0.00	0.00
Max. rep. pulling force	-	829	-	829	-	0.00

Table 3.258: *Results of benchmark 3-23, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	396.55	396.55	0.00
Max. allow. external pressure (long)	[kPa]	39.66	39.66	0.00
Int. pressure due to 100% filling (short)	[kPa]	600	600	0.00
Int. pressure due to 100% filling (long)	[kPa]	600	600	0.00

Use D-GEO PIPELINE input file bm3-23.dri to run this benchmark.

3.24 HDD with 2D geometry – Effect of traffic loads

3.24.1 Description

This benchmark checks the effect of two traffic loads on the stress analysis. The same input data's as for benchmark 3-1 (section 3.1) are used except that the Z co-ordinates of the top of the layers and the pipe configuration are divided by 10 in order to optimize the effect of the traffic load. The new geometry is given in Figure 3.12. The traffic loads have the following properties:

Traffic Load 1:
X co-ordinate at start 0 m
X co-ordinate at end 110 m
Load type Graph I
Traffic Load 2:
X co-ordinate at start 600 m
X co-ordinate at end 700 m
Load type Graph II

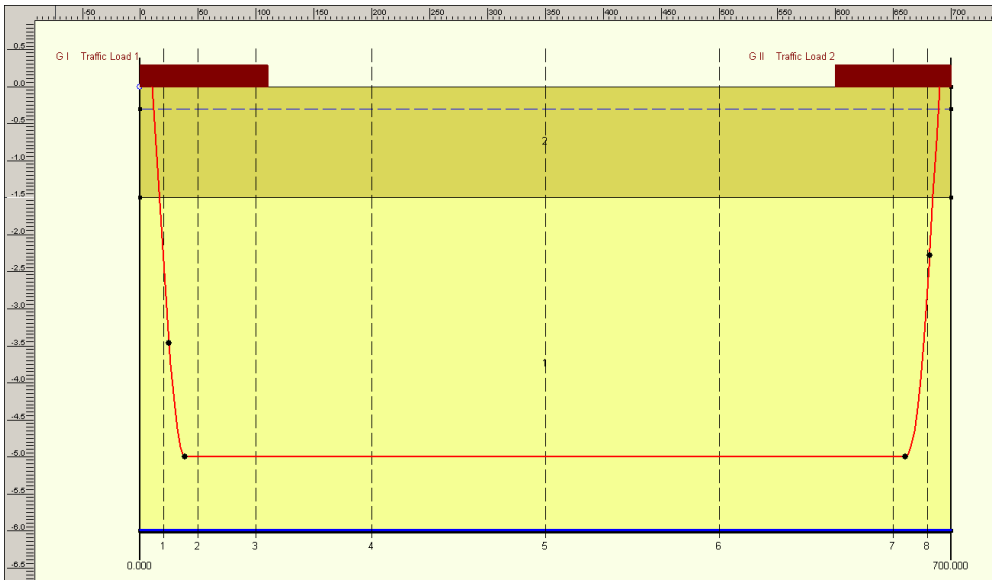

Figure 3.12: *Geometry of benchmark 3-12 with 2 traffic loads*

3.24.2 Analytical results

According to article C.5.1 from NEN 3650-1 (NEN, 2012a), the traffic load q_v is given by Figure 3.13, for both types of load and for four diameters: 200, 600, 1000 and 1600 mm.

Intermediary diameters are lineary interpolated. D-GEO PIPELINE uses the following formulas to convert this figure into numbers:

- For Graph I, ⊘ 200 mm: $q_v = 53.988 \times Z^{-1.058}$
- For Graph I, ⊘ 600 mm: $q_v = 51.403 \times Z^{-1.016}$
- For Graph I, ⊘ 1000 mm: $q_v = 46.522 \times Z^{-0.94}$
- For Graph I, ⊘ 1600 mm: $q_v = 39.448 \times Z^{-0.804}$
- For Graph II, ⊘ 200 mm: $q_v = 31.716 \times Z^{-1.457}$
- For Graph II, ⊘ 600 mm: $q_v = 29.501 \times Z^{-1.4}$
- For Graph II, ⊘ 1000 mm: $q_v = 26.776 \times Z^{-1.324}$
- For Graph II, ⊘ 1600 mm: $q_v = 21.963 \times Z^{-1.172}$

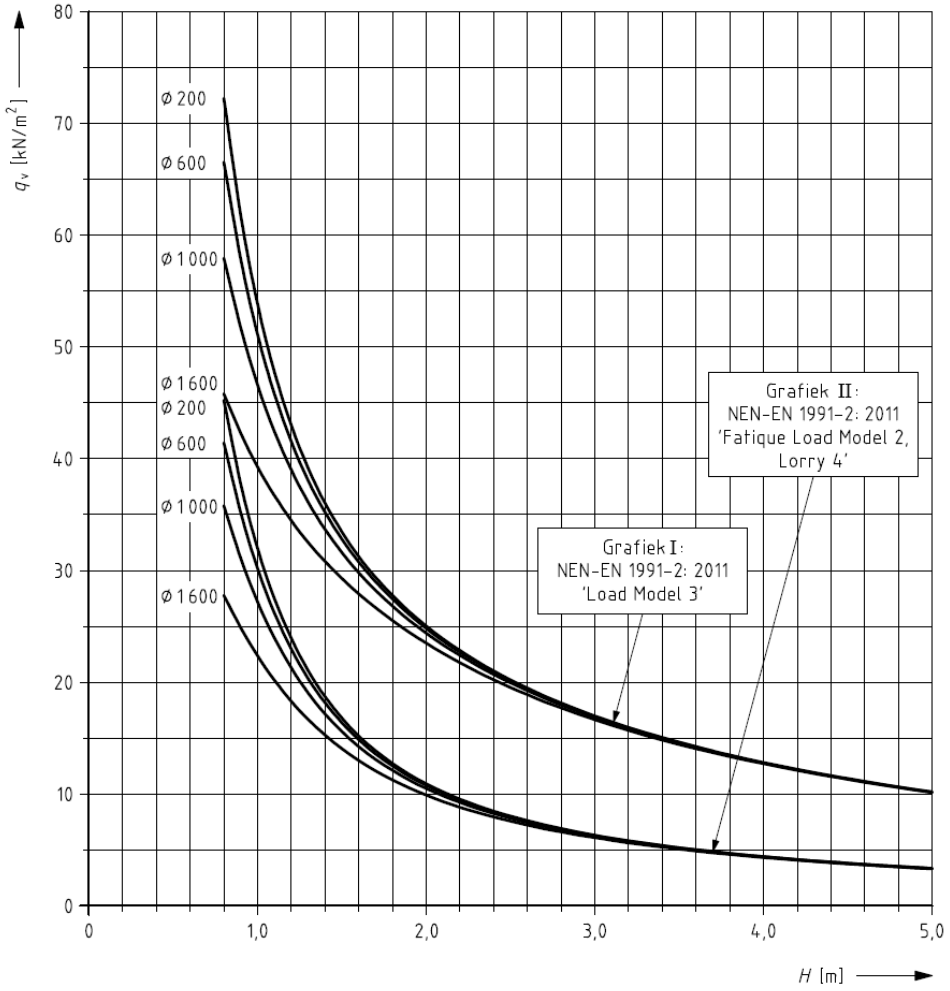

Figure 3.13: *Traffic load as a function of the depth, for different pipe diameters, according to NEN 3650-1*

In this benchmark, the pipe diameter is 800 mm, a linear interpolation between curves ⊘ 600 mm and ⊘ 1000 mm is performed and leads to the results given in Table 3.259.

Table 3.259: *Analytical results for the calculation of the traffic load*

		Traffic Load 1			Traffic Load 2		
Vert.	Z	$q_{v;\oslash 600}$	$q_{v;\oslash 1000}$	$q_{v;\oslash 800}$	$q_{v;\oslash 600}$	$q_{v;\oslash 1000}$	$q_{v;\oslash 800}$
[-]	[m]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]	[kN/m^2]
1	-1.986	34.556	32.949	33.752	n.a.	n.a.	n.a.
2	-4.686	14.448	14.705	14.576	n.a.	n.a.	n.a.
3	-4.686	14.448	14.705	14.576	n.a.	n.a.	n.a.
4	-4.686	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
5	-4.686	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
6	-4.686	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
7	-4.686	n.a.	n.a.	n.a.	4.582	4.677	4.63
8	-2.34	n.a.	n.a.	n.a.	12.113	11.728	11.92

Hereafter are some intermediate results used for the pulling force and the strength calculations:

Factor of friction pipe-roller	f_1	0.1	[-]
Friction pipe-mud	f_2	0.00005	[N/mm^2]
Factor of friction pipe-soil	f_3	0.2	[-]
Load factor - Design pressure	f_{pd}	1.25	[-]
Load factor - Design pressure (combination)	$f_{pd;comb}$	1.15	[-]
Load factor - Test pressure	f_{pt}	1.1	[-]
Load factor - Installation	$f_{install}$	1.1	[-]
Load factor - Soil load Qn	f_{Qn1}	1.5	[-]
Load factor - Temperature	f_{temp}	1.1	[-]
Contingency factor - E-modulus	f_E	1.25	[-]
Contingency factor - Pulling force	f_{pull}	1.4	[-]
Contingency factor - Modulus of subgrade reaction	f_{kv}	1.6	[-]
Contingency factor - Soil load Qn	f_{Qn2}	1.1	[-]
Contingency factor - Bending moment	f_M	1.27	[-]
Contingency factor - Bending radius	f_R	1.1	[-]
Contingency factor - Pressure borehole	$f_{press;bore}$	1.1	[-]
Factor of importance	S	1	[-]
Allowable deflection of pipe (Steel)		17	[%]
Piggability (Steel)		8	[%]
Allowable deflection of pipe (PE)		n.a.	[%]
Piggability (PE)		n.a.	[%]
Unit weight water	γ_w	10	[N/mm^3]
Safety factor cover (Drained layer)		0.67	[-]
Safety factor cover (Undrained layer)		0.5	[-]
Traffic load factor	f_{qv}	1.35	[-]
Effective weight of pipe	g_{eff}	1.414	[N/mm]
Weight of pipeline (incl. filling)	g_{fill}	0.456	[N/mm]
Uplift force	g_{upw}	5.529	[N/mm]
Moment coefficient indirect bottom	k_b'	0.083	[-]
Moment coefficient indirect top	k_t'	0.061	[-]
Moment coefficient direct bottom	k_b	0.138	[-]
Moment coefficient direct top	k_t	0.131	[-]
Direct deflection factor	k_y	0.089	[-]
Indirect deflection factor	k_y'	0.048	[-]
Part of pipe filled with water during pull back	P_{water}	10	[%]
Cross sections of the pipe	A	39769.979	[mm^2]

	A_{trek}	46618.093	[mm^2]
	A_{inw}	456036.731	[mm^2]
Minimal wall thickness	$d_{\mathrm{n;min}}$	16.15	[mm]
Outer radius of the pipeline	r_{e}	400	[mm]
Inner radius of the pipeline	r_{i}	381	[mm]
Average radius of the pipeline	r_{g}	390.5	[mm]
Moment of inertia of the pipe	I_{b}	3556505999	[mm^4]
Moment of inertia of the wall	I_{w}	571.583	[mm^3]
Pipe resisting moment	W_{b}	8891265	[mm^{4}m]
Wall resisting moment	W_{w}	60.167	[mm^{3}m]
Unit weight of drilling fluid	$\gamma_{\mathrm{drill\ fluid}}$	11	[kN/m^3]
Maximum modulus of subgrade reaction	$k_{\mathrm{v;max}}$	31637.947	[kN/m^3]
Maximum neutral vertical soil load	$q_{\mathrm{v;n;r;max}}$	57.835	[kN/m^2]
Maximum traffic load	$q_{\mathrm{T;max}}$	33.752	[kN/m^2]
Max. red. neutral vertical soil load (incl. traffic load)	$q_{\mathrm{v;n;r;maxT}}$	43.258	[kN/m^2]
Max. corrected red. soil load (without traffic load)	q_{n}	71.376	[kN/m^2]
Max. corrected red. soil load (incl. traffic load)	q_{nT}	95.427	[kN/m^2]
Maximum neutral horizontal soil load	$q_{\mathrm{h;n;r}}$	42.866	[kN/m^2]
Soil reaction - Left curve	$q_{\mathrm{r;left}}$	502.806	[kN/m^2]
Soil reaction - Right curve	$q_{\mathrm{r;right}}$	377.104	[kN/m^2]
Soil reaction - Left curve (long term)	$q_{\mathrm{r;left}}$	n.a.	[kN/m^2]
Soil reaction - Right curve (long term)	$q_{\mathrm{r;right}}$	n.a.	[kN/m^2]
Characteristic stiffness pipeline-soil	λ	0.0003049	[mm^{-1}]
Characteristic stiffness pipeline-soil (long term)	λ_{long}	n.a.	[mm^{-1}]

3.24.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.261: *Results of benchmark 3-24, Buoyancy control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	553	553	0.00
Weight of pipeline (incl. filling)	[kg/m]	412	412	0.00
Effective weight of pipe	[kg/m]	141	141	0.00

Table 3.262: *Results of benchmark 3-24, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	280	0	280	0.00	0.00
T2	15	280	15	280	0.00	0.00
T3	29	2026	29	2026	0.00	0.00
T4	651	2024	651	2024	0.00	0.00
T5	672	3437	672	3437	0.00	0.00
T6	681	3437	681	3437	0.00	0.00
Max. rep. pulling force	-	0	-	0	-	0.00

Table 3.263: *Results of benchmark 3-24, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	1265	1265	0.00
σ_t	[N/mm^2]	11	11	0.00
$\sigma_{a;max}$	[N/mm^2]	1276	1276	0.00
$\sigma_{V;max}$	[N/mm^2]	1276	1276	0.00

Table 3.264: *Results of benchmark 3-24, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	2108	2108	0.00
σ_t	[N/mm^2]	133	133	0.00
$\sigma_{a;max}$	[N/mm^2]	2241	2241	0.00
λ	[mm^{-1}]	0.000305	0.000305	0.00
q_r	[N/mm^2]	0.5028	0.5028	0.00
σ_{qr}	[N/mm^2]	217	217	0.00
$\sigma_{t;max}$	[N/mm^2]	217	217	0.00
$\sigma_{V;max}$	[N/mm^2]	2358	2358	0.00

Table 3.265: *Results of benchmark 3-24, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	18	18	0.00
σ_{px}	[N/mm^2]	9	9	0.00
σ_{ptest}	[N/mm^2]	22	22	0.00
σ_{pm}	[N/mm^2]	16	16	0.00

Table 3.266: *Results of benchmark 3-24, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	2108	2108	0.00
$\sigma_{a;max}$	[N/mm^2]	2108	2108	0.00
σ_{qr}	[N/mm^2]	217	217	0.00
σ_{qn}	[N/mm^2]	69	69	0.00
$\sigma_{t;max}$	[N/mm^2]	286	286	0.00
$\sigma_{V;max}$	[N/mm^2]	2265	2265	0.00

Table 3.267: *Results of benchmark 3-24, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	2108	2108	0.00
σ_{py}	[N/mm^2]	17	17	0.00
σ_{px}	[N/mm^2]	8	8	0.00
σ_{ptest}	[N/mm^2]	22	22	0.00
σ_{ptemp}	[N/mm^2]	26	26	0.00
$\sigma_{a;max}$	[N/mm^2]	2117	2117	0.00
σ_{qr}	[N/mm^2]	217	217	0.00
σ_{qn}	[N/mm^2]	69	69	0.00
$\sigma_{V;max}$	[N/mm^2]	2258	2258	0.00

Table 3.268: *Results of benchmark 3-24, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	235	235	0.00
σ_{py}	[N/mm^2]	213.64	213.64	0.00
σ_{pm}	[N/mm^2]	235	235	0.00
$\sigma_{V;max}$	[N/mm^2]	363.18	363.18	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.269: *Results of benchmark 3-24, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	12.1	12.1	0.00
Max. allowable	[mm]	136	136	0.00
Max. allow. (piggability)	[mm]	64	64	0.00

Table 3.270: *Results of benchmark 3-24, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Use D-GEO PIPELINE input file bm3-24.dri to run this benchmark.

3.25 HDD with safety factors from the European Standard CEN – Steel pipe

3.25.1 Description

This benchmark checks the use of the safety factors from the European Standard CEN in combination with a steel pipe. The same input data's as for benchmark 3-7a (section 3.7) are used except that the safety factors are different: when selecting the European Standard CEN, no factor is apllied on the loads. The choice of a different standard will have effects only on the strength calculation.

3.25.2 Analytical results

Hereafter are some intermediate results used for the pulling force and the strength calculations:

Factor of friction pipe-roller	f_1	0.2	[-]
Friction pipe-mud	f_2	0.00035	[N/mm^2]
Factor of friction pipe-soil	f_3	0.3	[-]
Load factor - Design pressure	f_{pd}	n.a	[-]
Load factor - Design pressure (combination)	$f_{pd;comb}$	n.a	[-]
Load factor - Test pressure	f_{pt}	n.a	[-]
Load factor - Installation	$f_{install}$	n.a	[-]
Load factor - Soil load Qn	f_{Qn1}	n.a	[-]
Load factor - Temperature	f_{temp}	n.a	[-]
Contingency factor - E-modulus	f_E	1.4	[-]
Contingency factor - Pulling force	f_{pull}	1.1	[-]
Contingency factor - Modulus of subgrade reaction	f_{kv}	1.1	[-]
Contingency factor - Soil load Qn	f_{Qn2}	1.2	[-]
Contingency factor - Bending moment	f_M	n.a	[-]
Contingency factor - Bending radius	f_R	1.3	[-]
Contingency factor - Pressure borehole	$f_{press;bore}$	1.15	[-]
Factor of importance	S	1	[-]
Allowable deflection of pipe (Steel)		17	[%]
Piggability (Steel)		8	[%]
Allowable deflection of pipe (PE)		n.a.	[%]
Piggability (PE)		n.a.	[%]
Unit weight water	γ_w	10	[N/mm^3]
Safety factor cover (Drained layer)		0.67	[-]
Safety factor cover (Undrained layer)		0.5	[-]
Traffic load factor	f_{qv}	1.35	[-]
Effective weight of pipe	g_{eff}	10.093	[N/mm]
Weight of pipeline (incl. filling)	g_{fill}	2.409	[N/mm]
Uplift force	g_{upw}	22.973	[N/mm]
Moment coefficient indirect bottom	k_b'	0.073	[-]
Moment coefficient indirect top	k_t'	0.056	[-]
Moment coefficient direct bottom	k_b	0.139	[-]
Moment coefficient direct top	k_t	0.139	[-]
Direct deflection factor	k_y	0.091	[-]
Indirect deflection factor	k_y'	0.043	[-]
Part of pipe filled with water during pull back	P_{water}	15	[%]
Cross sections of the pipe	A	121535.457	[mm^2]
	A_{trek}	161085.163	[mm^2]
	A_{inw}	1606060.704	[mm^2]
Minimal wall thickness	$d_{n;min}$	26.25	[mm]
Outer radius of the pipeline	r_e	750	[mm]
Inner radius of the pipeline	r_i	715	[mm]
Average radius of the pipeline	r_g	732.5	[mm]
Moment of inertia of the pipe	I_b	43240291745	[mm^4]
Moment of inertia of the wall	I_w	3572.917	[mm^3]
Pipe resisting moment	W_b	57653722	[mm^{4}m]
Wall resisting moment	W_w	204.167	[mm^{3}m]
Unit weight of drilling fluid	$\gamma_{drill\ fluid}$	13	[kN/m^3]
Maximum modulus of subgrade reaction	$k_{v;max}$	20467.554	[kN/m^3]
Maximum neutral vertical soil load	$q_{v;n;r;max}$	154.787	[kN/m^2]

Maximum traffic load	$q_{T;max}$	0	[kN/m^2]
Max. red. neutral vertical soil load (incl. traffic load)	$q_{v;n;r;maxT}$	154.787	[kN/m^2]
Max. corrected red. soil load (without traffic load)	q_{n}	185.744	[kN/m^2]
Max. corrected red. soil load (incl. traffic load)	q_{nT}	185.744	[kN/m^2]
Maximum neutral horizontal soil load	$q_{h;n;r}$	101.846	[kN/m^2]
Soil reaction - Left curve	$q_{r;left}$	52.606	[kN/m^2]
Soil reaction - Right curve	$q_{r;right}$	65.131	[kN/m^2]
Soil reaction - Left curve (long term)	$q_{r;left}$	n.a.	[kN/m^2]
Soil reaction - Right curve (long term)	$q_{r;right}$	n.a.	[kN/m^2]
Characteristic stiffness pipeline-soil	λ	0.0001771	[mm^{-1}]
Characteristic stiffness pipeline-soil (long term)	λ_{long}	n.a.	[mm^{-1}]

3.25.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.272: *Results of benchmark 3-25, Buoyancy Control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	2297	2297	0.00
Weight of pipeline (incl. filling)	[kg/m]	1288	1288	0.00
Effective weight of pipe	[kg/m]	1009	1009	0.00

Table 3.273: *Results of benchmark 3-25, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	4610	0	4610	0.00	0.00
T2	43	4701	43	4701	0.00	0.00
T3	338	6579	338	6579	0.00	0.00
T4	1441	14235	1441	14235	0.00	0.00
T5	1716	16676	1716	16676	0.00	0.00
T6	1790	16832	1790	16832	0.00	0.00
Max. rep. pulling force	-	3332	-	3332	-	0.00

Table 3.274: *Results of benchmark 3-25, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	220	220	0.00
σ_t	[N/mm^2]	42	42	0.00
$\sigma_{a;max}$	[N/mm^2]	262	262	0.00
$\sigma_{V;max}$	[N/mm^2]	262	262	0.00

Table 3.275: *Results of benchmark 3-25, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	251	251	0.00
σ_t	[N/mm^2]	152	152	0.00
$\sigma_{a;max}$	[N/mm^2]	404	404	0.00
λ	[mm^{-1}]	0.000177	0.000177	0.00
q_r	[N/mm^2]	0.0977	0.0977	0.00
σ_{qr}	[N/mm^2]	39	39	0.00
$\sigma_{t;max}$	[N/mm^2]	39	39	0.00
$\sigma_{V;max}$	[N/mm^2]	424	424	0.00

Table 3.276: *Results of benchmark 3-25, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	14	14	0.00
σ_{px}	[N/mm^2]	7	7	0.00
σ_{ptest}	[N/mm^2]	25	25	0.00
σ_{pm}	[N/mm^2]	12	12	0.00

Table 3.277: *Results of benchmark 3-25, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	251	251	0.00
$\sigma_{a;max}$	[N/mm^2]	251	251	0.00
σ_{qr}	[N/mm^2]	39	39	0.00
σ_{qn}	[N/mm^2]	140	140	0.00
$\sigma_{t;max}$	[N/mm^2]	178	178	0.00
$\sigma_{V;max}$	[N/mm^2]	374	374	0.00

Table 3.278: *Results of benchmark 3-25, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	251	251	0.00
σ_{py}	[N/mm^2]	14	14	0.00
σ_{px}	[N/mm^2]	7	7	0.00
σ_{ptest}	[N/mm^2]	25	25	0.00
σ_{ptemp}	[N/mm^2]	13	13	0.00
$\sigma_{a;max}$	[N/mm^2]	258	258	0.00
σ_{qr}	[N/mm^2]	39	39	0.00
σ_{qn}	[N/mm^2]	140	140	0.00
$\sigma_{V;max}$	[N/mm^2]	365	365	0.00

Table 3.279: *Results of benchmark 3-25, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	173.91	173.91	0.00
σ_{py}	[N/mm^2]	153.85	153.85	0.00
σ_{pm}	[N/mm^2]	169.23	169.23	0.00
$\sigma_{V;max}$	[N/mm^2]	278	278	0.00
$\sigma_{a/t}$ (short)	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (long)	[N/mm^2]	n.a.	n.a.	

Table 3.280: *Results of benchmark 3-25, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	10.5	10.5	0.00
Max. allowable	[mm]	255	255	0.00
Max. allow. (piggability)	[mm]	120	120	0.00

Table 3.281: *Results of benchmark 3-25, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	n.a.	n.a.	
Max. allow. external pressure (long)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (short)	[kPa]	n.a.	n.a.	
Int. pressure due to 100% filling (long)	[kPa]	n.a.	n.a.	

Use D-GEO PIPELINE input file bm3-25.dri to run this benchmark.

3.26 HDD with safety factors from the European Standard CEN – PE pipe

3.26.1 Description

This benchmark checks the use of the safety factors from the European Standard CEN in combination with a PE pipe. The same input data's as for benchmark 3-24 (section 3.24) are used except that a PE pipe is used instead of a steel pipe.

3.26.2 Analytical results

Hereafter are some intermediate results used for the pulling force and the strength calculations:

Factor of friction pipe-roller	f_1	0.2	[-]
Friction pipe-mud	f_2	0.00035	[N/mm^2]
Factor of friction pipe-soil	f_3	0.3	[-]
Load factor - Design pressure	f_{pd}	n.a	[-]
Load factor - Design pressure (combination)	$f_{pd;comb}$	n.a	[-]
Load factor - Test pressure	f_{pt}	n.a	[-]
Load factor - Installation	$f_{install}$	n.a	[-]
Load factor - Soil load Qn	f_{Qn1}	n.a	[-]
Load factor - Temperature	f_{temp}	n.a	[-]
Contingency factor - E-modulus	f_E	1.4	[-]
Contingency factor - Pulling force	f_{pull}	1.1	[-]

Contingency factor - Modulus of subgrade reaction	f_{kv}	1.1	[-]
Contingency factor - Soil load Qn	f_{Qn2}	1.2	[-]
Contingency factor - Bending moment	f_{M}	n.a	[-]
Contingency factor - Bending radius	f_{R}	n.a.	[-]
Contingency factor - Pressure borehole	$f_{press;bore}$	1.15	[-]
Factor of importance	S	1	[-]
Allowable deflection of pipe (Steel)		n.a.	[%]
Piggability (Steel)		n.a.	[%]
Allowable deflection of pipe (PE)		8	[%]
Piggability (PE)		5	[%]
Unit weight water	γ_w	10	[N/mm^3]
Safety factor cover (Drained layer)		0.67	[-]
Safety factor cover (Undrained layer)		0.5	[-]
Traffic load factor	f_{qv}	1.35	[-]
Effective weight of pipe	g_{eff}	4.874	[N/mm]
Weight of pipeline (incl. filling)	g_{fill}	0.585	[N/mm]
Uplift force	g_{upw}	6.535	[N/mm]
Moment coefficient indirect bottom	k_b'	0.073	[-]
Moment coefficient indirect top	k_t'	0.056	[-]
Moment coefficient direct bottom	k_b	0.139	[-]
Moment coefficient direct top	k_t	0.139	[-]
Direct deflection factor	k_y	0.091	[-]
Indirect deflection factor	k_y'	0.043	[-]
Part of pipe filled with water during pull back	P_{water}	15	[%]
Cross sections of the pipe	A	112735.141	[mm^2]
	A_{trek}	112735.141	[mm^2]
	A_{inw}	389919.683	[mm^2]
Minimal wall thickness	$d_{n;min}$	47.7	[mm]
Outer radius of the pipeline	r_e	400	[mm]
Inner radius of the pipeline	r_i	352.3	[mm]
Average radius of the pipeline	r_g	376.15	[mm]
Moment of inertia of the pipe	I_b	8007444342	[mm^4]
Moment of inertia of the wall	I_w	9044.278	[mm^3]
Pipe resisting moment	W_b	20018611	[mm^{4}m]
Wall resisting moment	W_w	379.215	[mm^{3}m]
Unit weight of drilling fluid	$\gamma_{drill\ fluid}$	13	[kN/m^3]
Maximum modulus of subgrade reaction	$k_{v;max}$	61938.505	[kN/m^3]
Maximum neutral vertical soil load	$q_{v;n;r;max}$	76.383	[kN/m^2]
Maximum traffic load	$q_{T;max}$	0	[kN/m^2]
Max. red. neutral vertical soil load (incl. traffic load)	$q_{v;n;r;maxT}$	76.383	[kN/m^2]
Max. corrected red. soil load (without traffic load)	q_n	91.659	[kN/m^2]
Max. corrected red. soil load (incl. traffic load)	q_{nT}	91.659	[kN/m^2]
Maximum neutral horizontal soil load	$q_{h;n;r}$	50.258	[kN/m^2]
Soil reaction - Left curve	$q_{r;left}$	3.087	[kN/m^2]
Soil reaction - Right curve	$q_{r;right}$	3.823	[kN/m^2]
Soil reaction - Left curve (long term)	$q_{r;left}$	1.381	[kN/m^2]
Soil reaction - Right curve (long term)	$q_{r;right}$	1.71	[kN/m^2]
Characteristic stiffness pipeline-soil	λ	0.0011153	[mm^{-1}]
Characteristic stiffness pipeline-soil (long term)	λ_{long}	0.0016677	[mm^{-1}]

3.26.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 3.283: *Results of benchmark 3-26, Buoyancy control*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error [%]**
Uplift forces	[kg/m]	653	654	0.15
Weight of pipeline (incl. filling)	[kg/m]	166	166	0.00
Effective weight of pipe	[kg/m]	487	488	0.21

Table 3.284: *Results of benchmark 3-26, Pulling forces in the pipeline*

	Benchmark		**D-GEO PIPELINE**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	594.34	0	594.34	0.00	0.00
T2	43.04	680.84	43.04	680.84	0.00	0.00
T3	338	1364.62	338	1364.62	0.00	0.00
T4	1440.63	4234.93	1440.63	4234.93	0.00	0.00
T5	1715.52	5116.67	1715.52	5116.67	0.00	0.00
T6	1789.79	5265.94	1789.79	5265.94	0.00	0.00
Max. rep. pulling force	-	860	-	860	-	0.00

Table 3.285: *Results of benchmark 3-26, Strength calculation for Combination 1A*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.5	0.5	0.00
σ_t	[N/mm^2]	5.8	5.8	0.00
$\sigma_{a;max}$	[N/mm^2]	6.12	6.12	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.286: *Results of benchmark 3-26, Strength calculation for Combination 1B*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.57	0.57	0.00
σ_t	[N/mm^2]	51.38	51.38	0.00
$\sigma_{a;max}$	[N/mm^2]	51.75	51.75	0.00
λ	[mm^{-1}]	0.001115	0.001115	0.00
q_r	[N/mm^2]	0.00573	0.00573	0.00
σ_{qr}	[N/mm^2]	0.33	0.33	0.00
$\sigma_{t;max}$	[N/mm^2]	0.33	0.33	0.00
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.287: *Results of benchmark 3-26, Strength calculation for Combination 2*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{py}	[N/mm^2]	4.75	4.75	0.00
σ_{px}	[N/mm^2]	2.38	2.38	0.00
σ_{ptest}	[N/mm^2]	6.6	6.6	0.00
σ_{pm}	[N/mm^2]	4.11	4.11	0.00

Table 3.288: *Results of benchmark 3-26, Strength calculation for Combination 3*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.11	0.11	0.00
$\sigma_{a;max}$	[N/mm^2]	0.07	0.07	0.00
σ_{qr}	[N/mm^2]	0.15	0.15	0.00
σ_{qn}	[N/mm^2]	10.11	10.26	1.48
$\sigma_{t;max}$	[N/mm^2]	6.67	6.76	1.35
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.289: *Results of benchmark 3-26, Strength calculation for Combination 4*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_b	[N/mm^2]	0.11	0.11	0.00
σ_{py}	[N/mm^2]	4.75	4.75	0.00
σ_{px}	[N/mm^2]	2.38	2.38	0.00
σ_{ptest}	[N/mm^2]	6.6	6.6	0.00
σ_{ptemp}	[N/mm^2]	0.36	0.36	0.00
$\sigma_{a;max}$	[N/mm^2]	2.45	2.45	0.00
σ_{qr}	[N/mm^2]	0.15	0.15	0.00
σ_{qn}	[N/mm^2]	10.11	10.26	1.48
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	

Table 3.290: *Results of benchmark 3-26, Maximum allowable stresses*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
σ_{ptest}	[N/mm^2]	6.4	6.4	0.00
σ_{py}	[N/mm^2]	5.04	5.04	0.00
σ_{pm}	[N/mm^2]	n.a.	n.a.	
$\sigma_{V;max}$	[N/mm^2]	n.a.	n.a.	
$\sigma_{a/t}$ (short)	[N/mm^2]	6.4	6.4	0.00
$\sigma_{a/t}$ (long)	[N/mm^2]	5.04	5.04	0.00

Table 3.291: *Results of benchmark 3-26, Deflection of the pipeline*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Rel. error [%]**
Calculated	[mm]	85.4	86.6	1.41
Max. allowable	[mm]	64	64	0.00
Max. allow. (piggability)	[mm]	44.8	44.8	0.00

Table 3.292: *Results of benchmark 3-26, Implosion*

Result	Unit	**Benchmark**	**D-GEO PIPELINE**	**Error**
Max. allow. external pressure (short)	[kPa]	303.46	303.46	0.00
Max. allow. external pressure (long)	[kPa]	30.35	30.35	0.00
Int. pressure due to 100% filling (short)	[kPa]	0	0	0.00
Int. pressure due to 100% filling (long)	[kPa]	0	0	0.00

Use D-GEO PIPELINE input file bm3-26.dri to run this benchmark.

4 Group 4: Benchmarks generated by D-GEO PIPELINE

This chapter contains benchmarks for which the reference results are generated using D-GEO PIPELINE.

4.1 HDD with 3D geometry – Check of the pulling direction

4.1.1 Description

This benchmark checks the pulling direction. The same input data's as for benchmark 3-7b (section 3.7) are used except that the geometry is inversed (mirror symmetry) and the pulling direction is from left to right instead of right to left. Results for the pulling forces are therefore expected to be the same.

4.1.2 D-GEO PIPELINE results

Both files give identical results.

Table 4.1: *Results of benchmark 4-01, Pulling forces in the pipeline*

	D-GEO PIPELINE (bm3-7b)		**D-GEO PIPELINE (bm4-1)**		**Relative error**	
Charac. points	Length	Force	Length	Force	Length	Force
	[m]	[kN]	[m]	[kN]	[%]	[%]
T1	0	4610	0	4610	0.00	0.00
T2	74	4766	74	4766	0.00	0.00
T3	349	6884	349	6884	0.00	0.00
T4	1452	14562	1452	14562	0.00	0.00
T5	1747	16745	1747	16745	0.00	0.00
T6	1790	16836	1790	16836	0.00	0.00
Max. rep. pulling force		20468		20467	-	0.00

Use D-GEO PIPELINE input file bm4-1.dri to run this benchmark.

5 Group 5: Benchmarks compared with other programs

These benchmarks are intended to verify specific features of D-GEO PIPELINE comparing D-GEO PIPELINE results with those from an other program.

5.1 Settlements according to Koppejan model

5.1.1 Description

The same input data's as benchmark 1-1 (section 3.1) are used, except that a trapezoidal load (γ_{unsat} = 17 kN/m^3 and γ_{sat} = 20 kN/m^3) is added at the top of the Clay layer as shown in Figure 5.1. A settlement calculation is performed using the Koppejan model with the parameters given in Table 5.1.

Table 5.1: *Koppejan's parameters (benchmark 5-1)*

Parameter	Unit	Sand	Clay
OCR	[-]	1.3	1.1
C_p	[-]	200	1.1
C_p'	[-]	100	10
C_s	[-]	500	200
C_s'	[-]	150	80

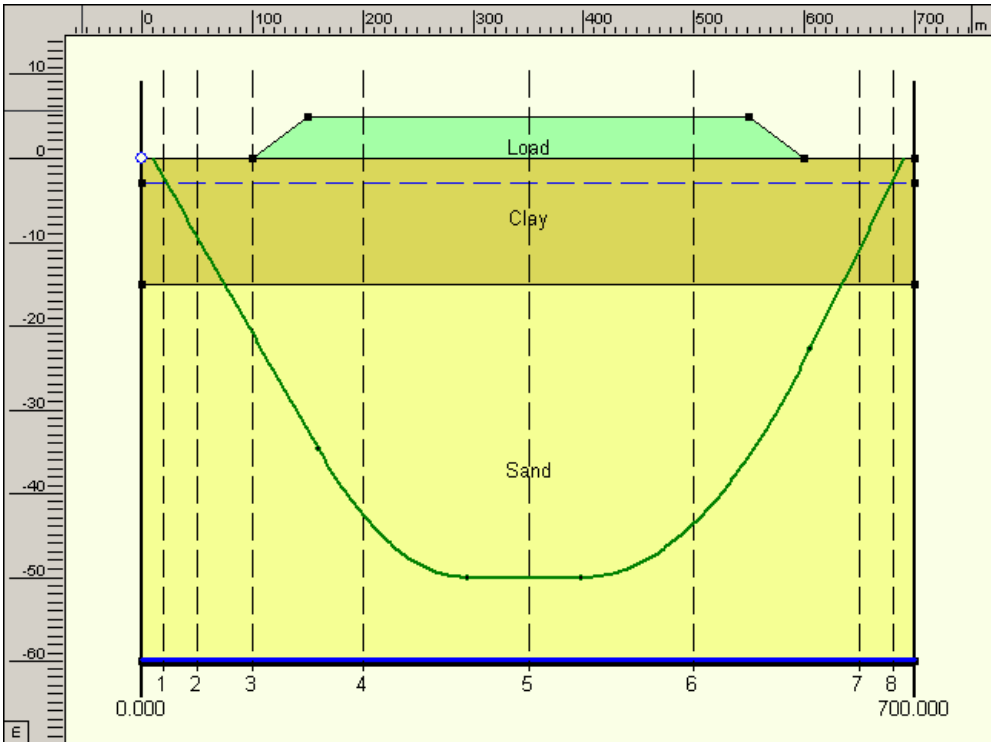

Figure 5.1: *Geometry of benchmark 5-1*

5.1.2 D-SETTLEMENT results

Benchmark results for the settlements calculation are calculated using the D-SETTLEMENT program (formally known as MSettle). Calculations are performed for 8 verticals and the results for each vertical are worked out in an Excel spreadsheet. A linear interpolation is used to get the settlement at the desired depth. Results are given in Table 5.2.

5.1.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 5.2: *Results of benchmark 5-01, Settlements according to Koppejan*

Vert.	Benchmark			D-GEO PIPELINE			Relative error		
nr.	Settl.	Add.	dv	Settl.	Add.	dv	Settl.	Add.	dv
[-]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[%]	[%]	[%]
1	1	5	6	1	5	6	0.00	0.00	0.00
2	2	10	12	2	10	12	0.00	0.00	0.00
3	21	20	41	21	20	41	0.00	0.00	0.00
4	35	50	85	35	50	85	0.00	0.00	0.00
5	18	50	68	18	50	68	0.00	0.00	0.00
6	32	20	52	32	20	52	0.00	0.00	0.00
7	2	10	12	2	10	12	0.00	0.00	0.00
8	1	5	6	1	5	6	0.00	0.00	0.00

Use D-GEO PIPELINE input file bm5-1.dri to run this benchmark.

5.2 Settlements according to Isotache model

5.2.1 Description

The same input data's as benchmark 1-1 (section 3.1) are used, except that a trapezoidal load (γ_{unsat} = 17 kN/m^3 and γ_{sat} = 20 kN/m^3) is added at the top of the Clay layer (see section 5.1). A settlement calculation is performed using the Isotache model with the parameters given in Table 5.3. Benchmark 5-2a uses an OCR parameter whereas benchmark 5-2b uses a POP parameter for the modelisation of the preconsolidation process.

Table 5.3: *Isotache's parameters (bm5-02)*

Parameter	Unit	Sand	Clay
OCR (bm5-2a)	[-]	1.3	1.1
POP (bm5-2b)	[kN/m^2]	15	20
a	[-]	0.005	0.001
b	[-]	0.05	0.01
c	[-]	0.005	0.001

5.2.2 D-SETTLEMENT results

Benchmark results for the settlements calculation are calculated using the D-SETTLEMENT program (formally known as MSettle). Calculations are performed for 8 verticals and the results for each vertical are worked out in an Excel spreadsheet. A linear interpolation is used to get the settlement at the desired Z depth. Results are given in Table 5.4 and Table 5.5.

5.2.3 D-GEO PIPELINE results

D-GEO PIPELINE results can be found in the *Report*.

Table 5.4: *Results of benchmark 5-02a, Settlements according to Isotache with OCR consolidation*

Vert.	**Benchmark**			**D-GEO PIPELINE**			**Relative error**		
nr.	Settl.	Add.	dv	Settl.	Add.	dv	Settl.	Add.	dv
[-]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[%]	[%]	[%]
1	1524	5	1529	1524	5	1529	0.00	0.00	0.00
2	1483	10	1493	1483	10	1493	0.00	0.00	0.00
3	1339	20	1359	1339	20	1359	0.00	0.00	0.00
4	702	50	752	702	50	752	0.00	0.00	0.00
5	397	50	447	397	50	447	0.00	0.00	0.00
6	659	20	679	659	20	679	0.00	0.00	0.00
7	1473	10	1483	1473	10	1483	0.00	0.00	0.00
8	1522	5	1527	1522	5	1527	0.00	0.00	0.00

Table 5.5: *Results of benchmark 5-02b, Settlements according to Isotache with POP consolidation*

Vert.	**Benchmark**			**D-GEO PIPELINE**			**Relative error**		
nr.	Settl.	Add.	dv	Settl.	Add.	dv	Settl.	Add.	dv
[-]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[%]	[%]	[%]
1	1891	5	1896	1891	5	1896	0.00	0.00	0.00
2	1867	10	1877	1867	10	1877	0.00	0.00	0.00
3	1695	20	1715	1695	20	1715	0.00	0.00	0.00
4	872	50	922	872	50	922	0.00	0.00	0.00
5	495	50	545	495	50	545	0.00	0.00	0.00
6	820	20	840	820	20	840	0.00	0.00	0.00
7	1859	10	1869	1859	10	1869	0.00	0.00	0.00
8	1890	5	1895	1890	5	1895	0.00	0.00	0.00

Use D-GEO PIPELINE input files bm5-2a.dri and bm5-2b.dri to run this benchmark.

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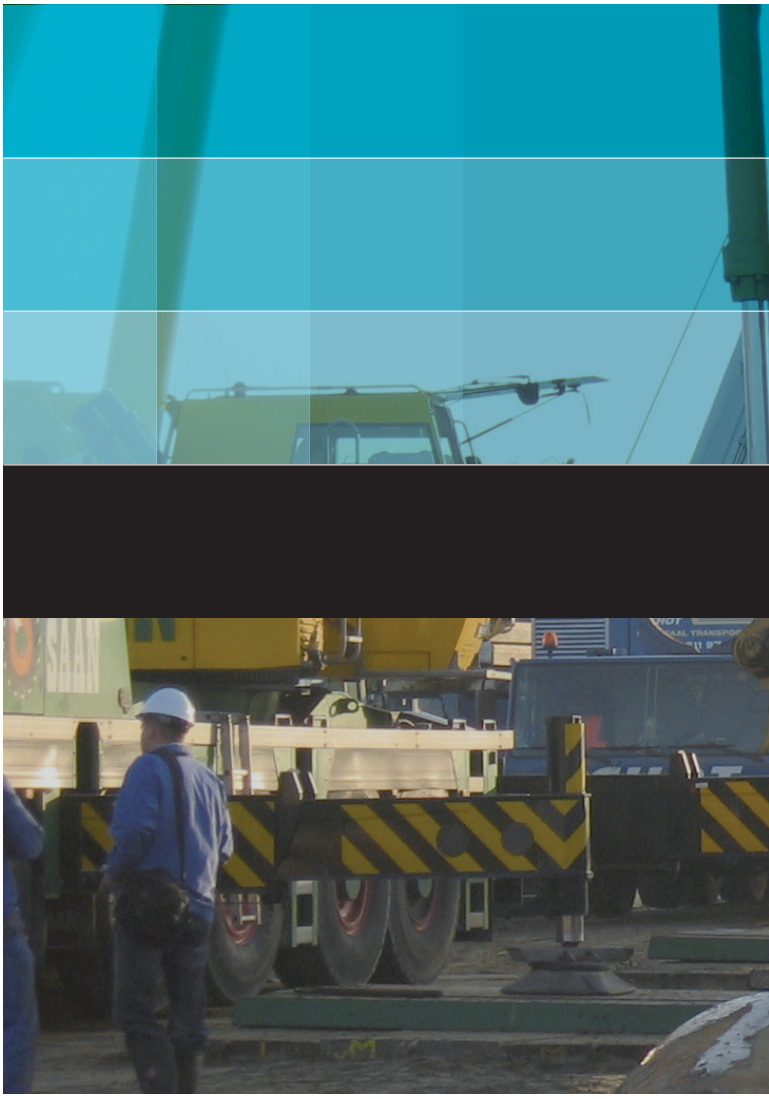

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