Client

Wintershall Noordzee BV

Project

D12-B to D15-FA-1 Pipeline Detailed Design

Document

Pipeline Detailed Design

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EXECUTIVE SUMMARY

Introduction

This Section presents the summary of the detailed design and engineering carried out for the 10-inch pipeline originating from the D12-B platform and terminating at the D15-FA-1 platform. The pipeline is located in the Dutch Sector of the North Sea and the governing design code is NEN 3656 (Ref.[1]).

Design Basis

The design basis prepared for the detailed engineering phase of the pipeline design is given in Ref. [i]

Pipeline Routing

The new 10" pipeline originates at the to be installed platform D12-B and terminates at D15-FA-1 platform. The pipeline should remain buried along it entire length as required by Ref. [1] and [13].

Near the D15-FA-1 platform a 36" NGT pipeline is crossed. This crossing is downstream of the pipeline target box and hence considered part of the spool piece and is not contained in this report.

The pipeline route is summarised in Table 1.

Table 1: Pipeline route data

ITEM	VALUE
Originating location	D12-B platform
Terminating location	D15-FA-1 platform
Approx. new pipeline length [km]	11.8
Water depth range [m LAT]	28.6 - 40 m

Along the proposed route, the sea bed is featureless with no sedimentary transports and the water depth increases from 28.6 to 40.0 m below LAT. In the vicinity of the D15-FA-1 platform a local variation of up to 1 m due to scour is present.

Fugro's geophysical survey of the route corridor identified the surface sediments as being mainly composed of a homogenous fine to medium sand.

Pipeline Wall Thickness Design

The pipe material to be used for the pipeline, spool pieces and hot bends is L360NB with a minimum yield stress of 360 N/mm2.

The minimum wall thickness of the pipeline has been determined using the design criteria outlined in NEN3656 (Ref. [1]). Table 2 below summarises the results of the analysis for sections of pipe inside (zone 1) and outside the 500 m zone (zones 2).

Table 2: Wall Thickness Design Summary

Parameter	Zone 1 (Inside 500 m Zone)	Zone 2 (Outside 500 m Zone)
Minimum WT for pressure containment (mm)	8.56	7.73
Minimum 5D bend WT for pressure containment (mm)	9.03	N/A(1)
Nominal WT required for pressure containment (mm)	11.56	10.73
Nominal 5D bend WT for pressure containment (mm)	12.03	N/A(1)
Selected Nominal WT (mm)	***12.7***	***12.7***
Note 1: There are no 5D bends outside the 500 m zone		

Detailed results can be found in Section 7. Detailed calculations can be found in Appendix A.

Pipeline On-bottom Stability Analysis

No concrete coating is to be applied to the pipeline. Therefore the selected wall thickness of the pipeline must provide the required submerged weight to ensure stability. Stability is achieved by ensuring that the pipeline has sufficient frictional resistance against lateral movement caused by wave and current induced hydrodynamic forces.

The pipeline must be stable in lateral direction on the seabed for 1-year returning environmental conditions. The pipeline will be buried before hydrostatic testing and operation and therefore not subjected to hydrodynamic loading during these periods. Hence the On-bottom stability analysis is carried out for the flooded installation condition.

The results of the analysis, giving the minimum required pipe weight for stability are summarised in Table 3. Detailed calculations can be found in Section 7.2 and Appendix B.

Table 3: On-bottom Stability Analysis – Results Summary

Property	**Installation Flooded**	
	Stability	**Liquefaction**
Pipe weight in air (kg/m)	133.1	133.1
Pipe content (kg/m)	49.4	49.4
Buoyancy (kg/m)	62.5	62.5
Available weight (kg/m)	70.6	133.1
Min. Required weight (kg/m)	58.4	91.2
CHECK	OK	OK

As can be seen from Table 3 the pipeline must be installed flooded to ensure lateral stability during the period of time between installation and pipeline burial.

Pipeline Free Span Analysis

Pipeline free span analysis has been carried out according to the requirements of NEN 3656 (Ref. [1]). The aim of the analysis was to determine the maximum allowable free span length of the pipelines.

The pipeline span assessment included the following items:

- Static span analysis
- Dynamic span analysis.

The static analysis concerns the determination of the pipe stresses under functional- and static environmental loads for a given span length. The dynamic span analysis is based on criteria for prevention of vortex induced vibrations (VIV) as out-lined in NEN 3656 (Ref. [1]) considering both current- and wave induced velocities.

Maximum allowable span lengths are determined for the installation, hydrotest and operational conditions. The results of the analysis are summarised in Table 4. Detailed results can be found in Section 8 and detailed calculation output can be found in Appendix C.

Table 4: Pipeline Free Span Analysis – Results Summary

Load Case	Max. Allowable Static Span Length (m)	Max. Allowable Dynamic Span Length (m)
Installation	45.3	13.8
Hydrotest	49.8	13.8
Operation – LC1	33.0	11.0
Operation – LC2	39.9	12.3

Pipeline Bottom roughness, Upheaval Buckling and Pre-sweeping Analysis

Due to the fact that the seabed along the pipeline is very flat and featureless, there is no issue with bottom roughness, i.e. no seabed preparations are required prior to pipelay.

The upheaval buckling analyses result in the combination of a minimum required imperfection length as a function of the imperfection height and soil cover height as given in table 5 and 6 for a pressure of 148 barg and a temperature of resp. 65 C. and 40 C. Appendix D shows the detailed calculations.

Table 5 Required length to accommodate an imperfection of given height for a given cover depth (pressure = 148 barg; temperature = 65 C.)

Min. required Imperfection Length (m)		Cover Height to TOP [m]													
		1.4	1.3	1.2	1.1	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Available Download, q [N/m]		6742	6059	5410	4794	4212	3662	3146	2664	2215	1799	1416	1067	751	469
Imperfection Height [m]	0.05	x	x	x	x	x	x	x	x	x	x	x	x	x	36
	0.1	x	x	x	x	x	x	x	x	x	x	x	32	44	58
	0.15	x	x	x	x	x	x	x	x	x	x	36	44	56	72
	0.2	x	x	x	x	x	x	x	x	32	38	46	54	66	84
	0.25	x	x	x	x	x	x	x	32	38	44	52	60	74	94
	0.3	x	x	x	x	x	x	34	38	44	50	58	68	80	>100
	0.35	x	x	x	x	x	34	38	42	48	54	62	72	88	>100
	0.4	x	x	x	x	34	38	42	46	52	58	68	78	94	>100
	0.45	x	x	x	32	38	42	46	50	56	62	72	84	100	>100
	0.5	x	x	32	36	40	44	48	54	60	66	76	88	>100	>100
	0.55	x	32	36	40	42	46	52	56	62	70	80	92	>100	>100
	0.6	x	34	38	42	46	50	54	60	66	74	84	96	>100	>100
	0.65	34	38	40	44	48	52	56	62	68	76	86	100	>100	>100
	0.7	36	40	42	46	50	54	58	64	72	80	90	>100	>100	>100
	0.75	38	42	44	48	52	56	62	68	74	82	94	>100	>100	>100
	0.8	40	44	46	50	54	58	64	70	76	86	96	>100	>100	>100
	0.85	42	44	48	52	56	60	66	72	80	88	100	>100	>100	>100
	0.9	44	46	50	54	58	62	68	74	82	90	>100	>100	>100	>100
	0.95	44	48	52	56	60	64	70	76	84	94	>100	>100	>100	>100
	1	46	50	54	56	62	66	72	78	86	96	>100	>100	>100	>100

Table 6 Required length to accommodate an imperfection of given height for a given cover depth (pressure = 148 barg; temperature = 40 C.)

Min. required Imperfection Length (m)		Cover Height to TOP [m]													
		1.4	1.3	1.2	1.1	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Available Download, q [N/m]		6742	6059	5410	4794	4212	3662	3146	2664	2215	1799	1416	1067	751	469
Imperfection Height [m]	0.05	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	0.1	x	x	x	x	x	x	x	x	x	x	x	x	x	38
	0.15	x	x	x	x	x	x	x	x	x	x	x	x	32	54
	0.2	x	x	x	x	x	x	x	x	x	x	x	30	48	64
	0.25	x	x	x	x	x	x	x	x	x	x	28	42	56	74
	0.3	x	x	x	x	x	x	x	x	x	28	38	50	62	80
	0.35	x	x	x	x	x	x	x	x	26	32	44	54	68	88
	0.4	x	x	x	x	x	x	x	x	30	40	50	60	74	94
	0.45	x	x	x	x	x	x	x	28	32	44	54	64	78	100
	0.5	x	x	x	x	x	x	26	30	40	48	58	68	82	>100
	0.55	x	x	x	x	x	x	28	32	44	52	60	72	86	>100
	0.6	x	x	x	x	x	26	30	40	48	56	64	76	92	>100
	0.65	x	x	x	x	24	30	32	44	50	58	68	78	96	>100
	0.7	x	x	x	x	28	30	40	46	54	60	70	82	98	>100
	0.75	x	x	x	26	30	32	44	50	56	64	72	86	>100	>100
	0.8	x	x	x	28	30	40	46	52	58	66	76	88	>100	>100
	0.85	x	x	26	30	32	42	48	54	60	68	78	92	>100	>100
	0.9	x	x	28	30	38	44	50	56	62	70	80	94	>100	>100
	0.95	x	26	28	32	40	46	52	58	64	72	82	96	>100	>100
	1	x	28	30	36	42	48	54	60	66	74	86	100	>100	>100

Pipeline Cathodic Protection Design

Per NEN 3656 the cathodic protection system of the pipeline will be designed as per ref. [12]. The cathodic protection will be designed to prevent external corrosion of the pipeline. The mass and spacing of the anodes has been determined such that the following criteria are met:

- Total anode mass to meet the mean and final current demand over the design life of the pipeline.
- Anode current output to meet the required current output at the end of the design life.
- Anode separation not to exceed a value of 300 m.

The characteristics of a typical anode element are given in Table 7.

Table 7: Typical anode characteristics

Item	Value
Type	Half Shell Bracelet
Material	Aluminium
Net Weight	16.5 [kg]
Cable connections	2 x @ 10” pipeline

Table 8 and Table 9 present the required number of anodes and the spacing between anodes. Detailed results of the calculation can be found in Section 11 and calculation output can be found in Appendix E.

Table 8: Cathodic Protection Anode spacing

Location	Anodes required (per nr. of joints)	Anode spacing [m]
KP 0.0 – KP 0.22	5 (1/3.6 joints)	43.9
KP 0.22 – KP 0.44	3 (1/6 joints)	73.2
KP 0.44 – KP 1.10	2 (1/9 joints)	109.8
KP 1.10 – End	1 (1/18 joints)	219.6

Table 9: Cathodic Protection System Summary

Total Required Net Anode Mass [kg]	Total Net Anode Mass Installed [kg]	Maximum final Current Demand [A]	Final Anode Current Output [A]	Total Number of Anodes(1,2)
912.2	1055.1	0.102	0.231	64
Note 1: total number of anodes is for pipeline only and does not include anodes on spool pieces Note 2: single half bracelet anode Net mass = 16.5 [kg] Note 3: valid for Temperature < 25 ^{0}C, local anode spacing may change due to temperature effects				

1. Introduction

1.1. General

Wintershall is planning to install a satellite platform, referred to as D12-B , in Block D12-A in the Dutch Sector of the North Sea. Export of the gas will be via a 10” pipeline to the D15-FA-1 platform. Platform D12-B will be operated by Wintershall and platform D15-FA-1 is operated by Neptune.

Additionally a future import pipeline (10”) is foreseen at D12-B.

For the new location Wintershall will take over topside E18-A operated by Wintershall, and will reuse this topside for the new location on the North Sea. The existing E18-A topside will be removed from the jacket, and it will be installed on the new D12-B jacket.

The platform will normally be unmanned.

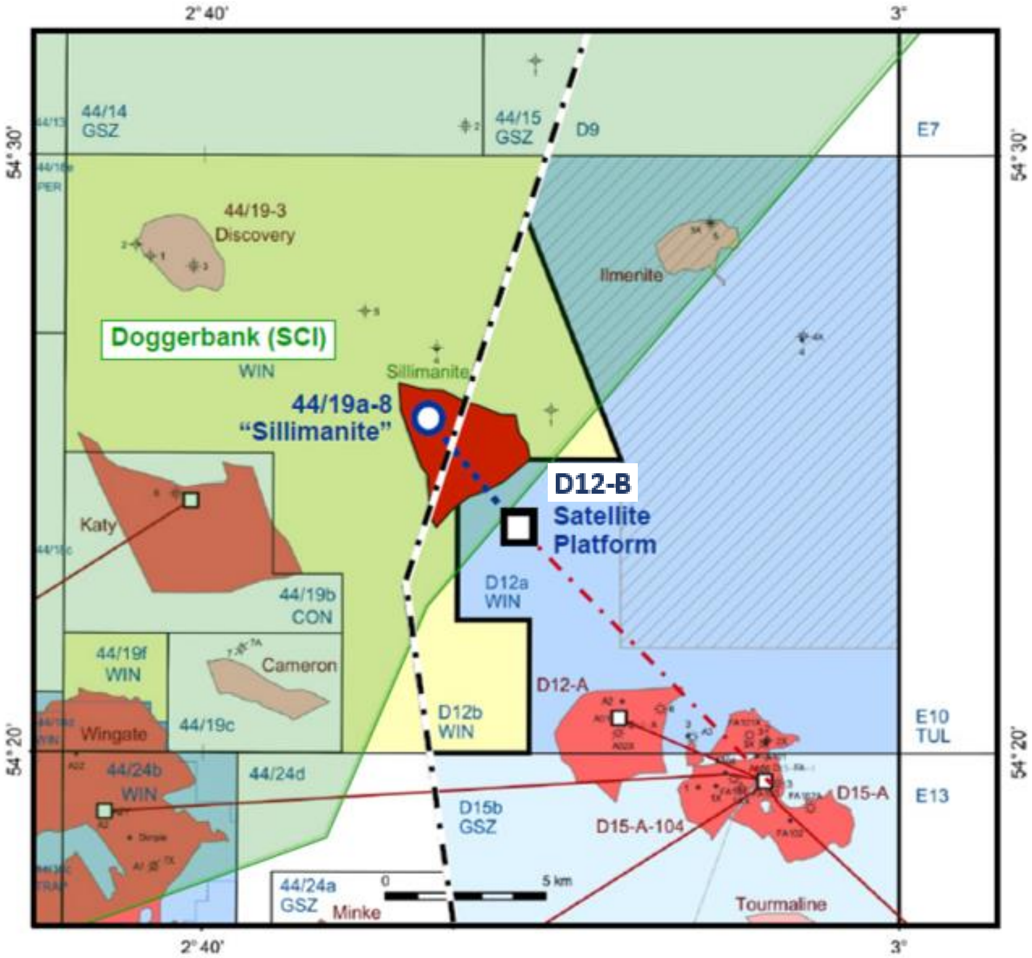


Figure 1-1 Sillimanite field licences & outline

1.2. Purpose Document

The objective of the current report is to present the pipeline design of the D12-B to D15-FA-1 pipeline, in accordance with NEN3656:2015 (Nederlands Normalisatie-instituut, 2012).

It is noted that the umbilical design is not part of the Enersea pipeline design scope, but is assumed to run parallel to the pipeline at a distance of 25m North of the pipeline. J-tubes are located at respectively the D12-B and D15-FA platform to accommodate platform entry.

The following engineering items are described in subsequent sections of this detailed design report:

- Regulations, Guidelines and Specifications
- Pipeline route data
- Design parameters
- Design Philosophy & criteria
- Wall thickness & on-bottom stability analysis
- Free span analysis
- Bottom roughness & upheaval buckling analysis
- Corrosion protection analysis

1.3. System of Units

All dimensions and calculations shall be documented using the International System of Units (SI) unless noted otherwise.

1.4. Abbreviations

BoD = Basis of Design

FEA = Finite Element Analysis

LAT = Lowest Astronomical Tide

MTO = Material Take Off

TB = Target Box

TOP = Top of Pipe

VIV = Vortex Induced Vibrations

2. Regulations, Guidelines and Specifications

The codes, regulations, guidelines and specifications used throughout the project are outlined in the following sections.

2.1. Regulations, Codes, Standards and Guidelines

[1] NEN3656:2015 “Eisen voor stalen buisleidingsystemen op zee” December 2015

[2] DNV-OS-F101. “Submarine Pipeline Systems.” October 2010.

[3] DNV-RP-F105. “Free Spanning Pipelines.” February 2006.

[4] DNV RP-F107. “Risk Assessment of Pipeline Protection.” October 2010.

[5] DNV-RP-F109. “On-Bottom Stability Design of Submarine Pipelines.” October 2010.

[6] DNV-RP-F110. “Global Buckling of Submarine Pipelines. Structural Design due to High Temperature/High Pressure.” October 2007.

[7] DNV-RP-C203. “Fatigue Design of Offshore Steel Structures.” April 2010.

[8] DNV-RP-C204. “Design against accidental loads.” November 2014.

[9] American Lifelines Alliance. “Guidelines for the Design of Buried Steel Pipe. ASCE July 2001.

[10] -

[11] Design of Submarine Pipelines Against Upheaval Buckling OTC 6335 by A.C. Palmer e.a. May 1990

[12] ISO 15589-2. “Petroleum petrochemical and natural gas industries — Cathodic protection of pipeline transportation systems - Part 2: Offshore pipelines” 2nd edition - 2012

[13] State Supervision of the Mines 1/2/3

2.2. Project Reference Documents

[i] Enersea report D12B-67031002-PL-AA7704-GLOBAL-001, rev. 02 “Basis of Design”

[ii] Enersea report D12B-67031002-PL-LA6958-GLOBAL-001, rev. 01 “Pipeline route selection”

2.3. Company Engineering Standards and Specifications

[a] Wintershall specification “CPE-PL-PS-020-02 - Project specification for pipeline external neoprene coating”

3. Pipeline route data

For a detailed description of the routing including alignment sheets, reference is made to [ii].

4. Pipeline Design Parameters

This chapter describes the pipe data and material properties as well as the product and operational data. All data has been taken from Ref. [i] unless noted otherwise.

4.1. Pipe and Material Data

The basic line pipe design data to be considered in the analysis for the 10" export gas line is presented in Table 4-1.

Property	10" Pipeline D12-B to D15-FA
Product transported	Natural gas
Design life [yrs]	Min. 30
Approx. length [km]	11.8
Steel material grade	L360NB
Manufacturing process	HFIW Carbon steel
Pipe outside diameter (")	10" OD
Pipe outside diameter (mm)	273.1
Nominal Wall thickness [mm]	12.7
Wall thickness tolerance [%]	+5.5% / -5.5%
Internal corrosion allowance [mm]	3
Anti-corrosion coating	Polyethylene
Anti-corrosion coating thickness [mm]	2.8
Anti-corrosion coating density [kg/m3]	900
Concrete weight coating thickness [mm]	N/A
Minimum subsea hot bend radius [m]	1.366 (5D)

Table 4-1 Pipeline data

Steel material properties considered in the design are presented in Table 4-2.

Property	Value
Material	L360NB
Density [kg/m3]	7850
Specified Minimum Yield Strength @20 °C [MPa]	360
Specified Minimum Yield Strength @100 °C [MPa]	304
Specified Minimum Yield Strength @65 °C [MPa]	343.2
Specified Minimum Yield Strength @90 °C [MPa]	315.2
Specified Minimum Tensile Strength [MPa]	460
Young's modulus [Pa]	2.07×10^{11}
Poisson ratio [-]	0.3
Thermal expansion coefficient [m/m·ºC]	1.17×10^{-5}

Table 4-2 Steel material properties

4.2. Process conditions

Table 4-3 presents the pipeline, riser and spool design process parameters considered in the analysis.

Property	10" export gas line
Design pressure	148 barg
Hydrotest pressure	202 barg
D12-B inlet Design temperature	65 °C
Ambient (air / surface) temperature	+4 °C
Content oil density	100 kg/m^3

Table 4-3 Process design parameters

Figure 4-1 shows the operational thermal profile along the pipeline.

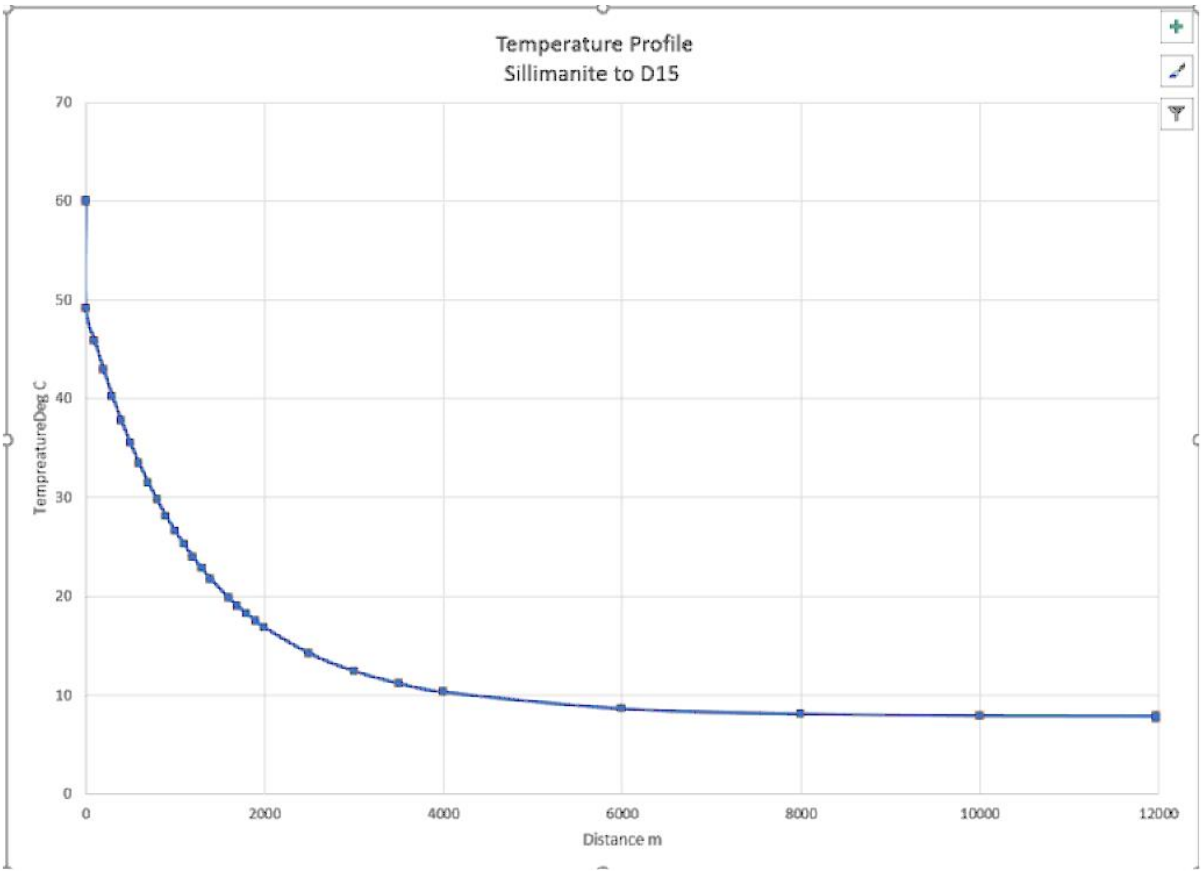


Figure 4-1 Operational thermal profile

4.3. Environmental data

4.3.1. Water Depth

The water depth range along the route is shown in Table 4-4

Table 4-4: Water depths

Property	Value
Minimum water depth along route (m LAT)	28.6
Maximum water depth along route (m LAT)	40.0

4.3.2. Wave & Current Data

For the detailed target box to target box design of the pipeline, environmental data has been taken from Ref. [i].

Tables 4-5 through 4-9 present the wave and current data at the D12-B location.

Table 4-5 Wave and current data - summarized

Property	1-year return period	10-year return period	100-year return period
Wave direction	Omni-directional	Omni-directional	Omni-directional
Maximum wave height (H_{max}) [m]	12.0	14.7	17.2
Associated wave period (T_{ass}) [s]	10.1	11.1	12.1
Significant wave height (H_s) [m]	6.5	7.9	9.3
Zero crossing period (T_z) [s]	8.3	9.1	9.9
Current direction	Omni-directional	Omni-directional	Omni-directional
Near-surface current speed [m/s]	0.91	0.98	1.05
Mid-depth current speed [m/s]	0.91	0.98	1.05
Near-bed current speed [m/s]	0.62	0.67	0.72
Positive surge & tidal levels (MSL) [m]	3.33	3.51	3.73
Negative surge & tidal levels (MSL) [m]	-0.85	-1.02	-1.24

Table 4-6 Independent Directional Extreme Wave Heights and Associated Periods

Direction from (relative to True North) – part 1

Return Period	Hs	Tz			Tp			Tass			Hmax	Crest Height
		(lower)	(central)	(upper)	(lower)	(central)	(upper)	(lower)	(central)	(upper)		
	(m)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(m)	(m)
1-year												
N	6.2	7.2	8.1	9.6	9.4	10.9	14.3	8.5	9.8	12.9	11.4	7.4
NE	5.0	6.5	7.3	8.6	8.5	9.9	12.8	7.7	8.9	11.5	9.3	6.0
E	5.6	6.8	7.7	9.1	8.9	10.4	13.6	8.0	9.4	12.2	10.4	6.7
SE	4.6	6.2	7.0	8.2	8.1	9.5	12.3	7.3	8.6	11.1	8.6	5.5
S	6.0	7.1	8.0	9.4	9.3	10.8	14.1	8.4	9.7	12.7	11.1	7.1
SW	6.1	7.1	8.0	9.5	9.3	10.8	14.1	8.4	9.7	12.7	11.3	7.3
W	6.5	7.4	8.3	9.8	9.6	11.2	14.6	8.6	10.1	13.1	12.0	7.7
NW	6.3	7.2	8.2	9.6	9.5	11.1	14.4	8.6	10.0	13.0	11.7	7.6
10-years												
N	7.6	8.0	9.0	10.6	10.4	12.2	15.8	9.4	11.0	14.2	14.0	9.0
NE	6.1	7.1	8.0	9.5	9.3	10.8	14.1	8.4	9.7	12.7	11.3	7.3
E	6.9	7.6	8.5	10.1	9.9	11.5	15.0	8.9	10.4	13.5	12.7	8.2
SE	5.7	6.9	7.8	9.2	9.0	10.5	13.7	8.1	9.5	12.3	10.5	6.8
S	7.3	7.8	8.8	10.4	10.2	11.9	15.5	9.2	10.7	14.0	13.6	8.7
SW	7.5	7.9	8.9	10.5	10.3	12.0	15.7	9.3	10.8	14.1	13.8	8.9
W	7.9	8.1	9.1	10.8	10.6	12.3	16.0	9.5	11.1	14.4	14.7	9.5
NW	7.8	8.1	9.1	10.7	10.6	12.3	16.0	9.5	11.1	14.4	14.4	9.3
50-years												
N	8.5	8.4	9.5	11.2	11.0	12.8	16.7	9.9	11.5	15.0	15.7	10.1
NE	6.9	7.6	8.5	10.1	9.9	11.5	15.0	8.9	10.4	13.5	12.7	8.2
E	7.7	8.0	9.0	10.7	10.4	12.2	15.8	9.4	11.0	14.2	14.3	9.2
SE	6.4	7.3	8.2	9.7	9.5	11.1	14.4	8.6	10.0	13.0	11.8	7.6
S	8.2	8.3	9.3	11.0	10.8	12.6	16.4	9.7	11.3	14.8	15.2	9.8
SW	8.4	8.4	9.4	11.1	10.9	12.7	16.5	9.8	11.4	14.9	15.5	10.0
W	8.9	8.6	9.7	11.5	11.3	13.1	17.1	10.2	11.8	15.4	16.4	10.6
NW	8.7	8.5	9.6	11.3	11.1	13.0	16.9	10.0	11.7	15.2	16.1	10.4

Table 4-7 Independent Directional Extreme Wave Heights and Associated Periods

Direction from (relative to True North) – part 2

Return Period	Hs	Tz			Tp			Tass			Hmax	Crest Height
		(lower)	(central)	(upper)	(lower)	(central)	(upper)	(lower)	(central)	(upper)		
	(m)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(m)	(m)
100-years												
N	8.9	8.6	9.7	11.5	11.3	13.1	17.1	10.2	11.8	15.4	16.4	10.6
NE	7.2	7.7	8.7	10.3	10.1	11.7	15.3	9.1	10.5	13.8	13.3	8.6
E	8.1	8.2	9.3	10.9	10.8	12.6	16.4	9.7	11.3	14.8	14.9	9.6
SE	6.7	7.5	8.4	9.9	9.7	11.3	14.8	8.7	10.2	13.3	12.3	8.0
S	8.6	8.5	9.5	11.3	11.0	12.8	16.7	9.9	11.5	15.0	15.9	10.3
SW	8.8	8.6	9.6	11.4	11.1	13.0	16.9	10.0	11.7	15.2	16.2	10.5
W	9.3	8.8	9.9	11.7	11.5	13.4	17.4	10.4	12.1	15.7	17.2	11.1
NW	9.1	8.7	9.8	11.6	11.4	13.2	17.2	10.3	11.9	15.5	16.9	10.9
1,000-years												
N	10.1	9.2	10.3	12.2	11.9	13.9	18.1	10.7	12.5	16.3	18.8	12.1
NE	8.2	8.3	9.3	11.0	10.8	12.6	16.4	9.7	11.3	14.8	15.2	9.8
E	9.2	8.8	9.9	11.6	11.5	13.4	17.4	10.4	12.1	15.7	17.1	11.0
SE	7.6	8.0	9.0	10.6	10.4	12.2	15.8	9.4	11.0	14.2	14.1	9.1
S	9.8	9.0	10.2	12.0	11.8	13.8	18.0	10.6	12.4	16.2	18.2	11.7
SW	10.0	9.1	10.3	12.1	11.9	13.9	18.1	10.7	12.5	16.3	18.5	12.0
W	10.6	9.4	10.6	12.5	12.3	14.3	18.7	11.1	12.9	16.8	19.7	12.7
NW	10.4	9.3	10.5	12.4	12.2	14.2	18.5	11.0	12.8	16.7	19.3	12.4
10,000-years												
N	11.4	9.7	11.0	13.0	12.8	14.9	19.4	11.5	13.4	17.5	21.0	13.6
NE	9.2	8.8	9.9	11.6	11.5	13.4	17.4	10.4	12.1	15.7	17.1	11.0
E	10.3	9.3	10.4	12.3	12.1	14.0	18.3	10.9	12.6	16.5	19.1	12.4
SE	8.5	8.4	9.5	11.2	11.0	12.8	16.7	9.9	11.5	15.0	15.8	10.2
S	11.0	9.6	10.8	12.7	12.5	14.6	19.0	11.3	13.1	17.1	20.4	13.2
SW	11.2	9.7	10.9	12.8	12.6	14.7	19.2	11.3	13.2	17.3	20.8	13.4
W	11.9	10.0	11.2	13.2	13.0	15.1	19.7	11.7	13.6	17.7	22.1	14.2
NW	11.7	9.9	11.1	13.1	12.9	15.0	19.5	11.6	13.5	17.6	21.6	14.0

Table 4-8 Profiles of Independent Direction Extreme Total Current Speed (m/s)

Directions are towards – part 1

Height Above Sea Bed	N	NE	E	SE	S	SW	W	NW	Omni
1 Year	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*	*m/s*
Surface	0.42	0.45	0.64	0.84	0.91	0.55	0.55	0.52	0.91
75% of Water Depth	0.42	0.45	0.64	0.84	0.91	0.55	0.55	0.52	0.91
50% of Water Depth	0.42	0.45	0.64	0.84	0.91	0.55	0.55	0.52	0.91
40% of Water Depth	0.40	0.43	0.62	0.80	0.87	0.54	0.52	0.49	0.87
30% of Water Depth	0.39	0.41	0.60	0.77	0.84	0.52	0.51	0.48	0.84
20% of Water Depth	0.37	0.39	0.56	0.73	0.79	0.48	0.48	0.45	0.79
10% of Water Depth	0.33	0.36	0.52	0.67	0.73	0.45	0.44	0.41	0.73
5% of Water Depth	0.29	0.31	0.44	0.57	0.62	0.38	0.38	0.35	0.62
Near Bed	0.29	0.31	0.44	0.57	0.62	0.38	0.38	0.35	0.62
10 Years									
Surface	0.46	0.48	0.69	0.90	0.98	0.60	0.59	0.56	0.98
75% of Water Depth	0.46	0.48	0.69	0.90	0.98	0.60	0.59	0.56	0.98
50% of Water Depth	0.46	0.48	0.69	0.90	0.98	0.60	0.59	0.56	0.98
40% of Water Depth	0.44	0.47	0.67	0.86	0.94	0.58	0.56	0.53	0.94
30% of Water Depth	0.42	0.45	0.65	0.84	0.91	0.56	0.55	0.52	0.91
20% of Water Depth	0.40	0.42	0.61	0.79	0.86	0.52	0.51	0.48	0.86
10% of Water Depth	0.36	0.39	0.56	0.72	0.79	0.48	0.48	0.45	0.79
5% of Water Depth	0.31	0.33	0.48	0.62	0.67	0.41	0.41	0.38	0.67
Near Bed	0.31	0.33	0.48	0.62	0.67	0.41	0.41	0.38	0.67
50 Years									
Surface	0.48	0.51	0.73	0.95	1.03	0.63	0.62	0.59	1.03
75% of Water Depth	0.48	0.51	0.73	0.95	1.03	0.63	0.62	0.59	1.03
50% of Water Depth	0.48	0.51	0.73	0.95	1.03	0.63	0.62	0.59	1.03
40% of Water Depth	0.46	0.49	0.70	0.91	0.99	0.61	0.59	0.56	0.99
30% of Water Depth	0.44	0.47	0.68	0.88	0.96	0.59	0.58	0.55	0.96
20% of Water Depth	0.42	0.44	0.64	0.83	0.90	0.55	0.54	0.51	0.90
10% of Water Depth	0.38	0.41	0.59	0.76	0.83	0.51	0.50	0.47	0.83
5% of Water Depth	0.33	0.35	0.50	0.65	0.71	0.43	0.43	0.40	0.71
Near Bed	0.33	0.35	0.50	0.65	0.71	0.43	0.43	0.40	0.71

Table 4-9 Profiles of Independent Direction Extreme Total Current Speed (m/s)

Directions are towards – part 2

Height Above Sea Bed	N	NE	E	SE	S	SW	W	NW	Omni
100 Years									
Surface	0.49	0.52	0.74	0.97	1.05	0.64	0.63	0.60	1.05
75% of Water Depth	0.49	0.52	0.74	0.97	1.05	0.64	0.63	0.60	1.05
50% of Water Depth	0.49	0.52	0.74	0.97	1.05	0.64	0.63	0.60	1.05
40% of Water Depth	0.47	0.50	0.71	0.93	1.01	0.62	0.60	0.57	1.01
30% of Water Depth	0.45	0.48	0.69	0.90	0.98	0.60	0.59	0.56	0.98
20% of Water Depth	0.43	0.45	0.65	0.85	0.92	0.56	0.55	0.52	0.92
10% of Water Depth	0.39	0.42	0.60	0.78	0.85	0.52	0.51	0.48	0.85
5% of Water Depth	0.34	0.36	0.51	0.66	0.72	0.44	0.44	0.41	0.72
Near Bed	0.34	0.36	0.51	0.66	0.72	0.44	0.44	0.41	0.72
1,000 Years									
Surface	0.53	0.56	0.80	1.05	1.13	0.69	0.68	0.65	1.13
75% of Water Depth	0.53	0.56	0.80	1.05	1.13	0.69	0.68	0.65	1.13
50% of Water Depth	0.53	0.56	0.80	1.05	1.13	0.69	0.68	0.65	1.13
40% of Water Depth	0.51	0.54	0.77	1.00	1.09	0.67	0.65	0.62	1.09
30% of Water Depth	0.48	0.52	0.75	0.97	1.06	0.65	0.64	0.61	1.06
20% of Water Depth	0.46	0.48	0.70	0.91	0.99	0.61	0.59	0.56	0.99
10% of Water Depth	0.42	0.45	0.65	0.84	0.91	0.56	0.55	0.52	0.91
5% of Water Depth	0.36	0.39	0.55	0.72	0.78	0.47	0.47	0.44	0.78
Near Bed	0.36	0.39	0.55	0.72	0.78	0.47	0.47	0.44	0.78
10,000 Years									
Surface	0.56	0.60	0.85	1.11	1.21	0.74	0.73	0.69	1.21
75% of Water Depth	0.56	0.60	0.85	1.11	1.21	0.74	0.73	0.69	1.21
50% of Water Depth	0.56	0.60	0.85	1.11	1.21	0.74	0.73	0.69	1.21
40% of Water Depth	0.54	0.57	0.82	1.06	1.16	0.71	0.69	0.66	1.16
30% of Water Depth	0.51	0.55	0.80	1.03	1.12	0.69	0.68	0.64	1.12
20% of Water Depth	0.49	0.51	0.75	0.97	1.05	0.64	0.63	0.60	1.05
10% of Water Depth	0.44	0.48	0.69	0.89	0.97	0.60	0.59	0.55	0.97
5% of Water Depth	0.39	0.41	0.59	0.76	0.83	0.50	0.50	0.47	0.83
Near Bed	0.39	0.41	0.59	0.76	0.83	0.50	0.50	0.47	0.83

4.3.3. Wave and current data summarized

The current velocities and wave properties presented can be converted to velocities at the top of pipe position. For the dynamic span and on-bottom stability analyses the water velocity perpendicular to the pipe are required. A sensitivity analyses for the wave/current direction has been carried out to determine the governing maximum horizontal particle velocity. see table 4-10 and 4-11 for the 1 and 100 year results

Table 4-10 Velocities bearing 140, 1-year return period

Wave/current from:	N	NE	E	SE	S	SW	W	NW
Current @ sea bed (m/s)	0.62	0.38	0.38	0.35	0.29	0.31	0.44	0.57
Perpendicular Wave speed Hmax (m/s)	1.73	1.86	1.67	0.14	1.47	2.33	2.07	0.24
Perpendicular Wave speed Hs (m/s)	0.94	0.90	0.80	0.07	0.69	***1.11***	1.04	0.13

Table 4-11 Velocities bearing 140, 100-year return period

Wave/current from:	N	NE	E	SE	S	SW	W	NW
Current @ sea bed (m/s)	0.72	0.44	0.44	0.41	0.34	0.36	0.51	0.66
Perpendicular Wave speed Hmax (m/s)	2.76	3.06	2.75	0.24	2.40	3.95	3.32	0.38
Perpendicular Wave speed Hs (m/s)	1.51	1.56	1.42	0.12	1.21	***1.94***	1.73	0.20

Based on the results above, the data for the SW direction is used and conservatively taken to have an angle of attack of 90^0 to the pipeline axis. Note that the difference in direction (from vs towards) for the waves and current have been accounted for.

4.4. Geotechnical data

The assumed soil properties are listed in Table 4-12 and recommended values as per DNV-RP-F105 (Ref. [3]) based on the soil general description.

Table 4-12 Assumed soil geotechnical properties

Soil type	Applicable area	Submerged Unit Weight (kN/m³)	Angle of internal friction (°)
Loose fine to medium sand	Pipe on surface	10	34
Loose fine sand	Trench backfill	8.5	28
Rock dump	Crossing / Tie-in	10	40

5. Design Philosophy

The pipeline is to be designed in accordance with the codes, standards and specifications as detailed in Chapter 2 of which the NEN3656 (ref. [1]) is leading.

Loads on submarine pipeline systems are generally caused by:

- pressure;
- temperature;
- soil;
- weight;
- environmental loading;
- adjacent structures;
- vibrations;
- loads due to installation;

5.1. Design phases

In the design of the submarine pipeline, the following phases may be distinguished:

- gathering relevant design data;
- dividing pipeline into sections;
- establishing loads and design factors;
- calculation of forces and moments;
- calculation of stresses and where relevant associated strains and displacements;
- checking stresses, strains and deflections against allowable values;

5.2. Loads

The loads applied to the submarine pipeline system may be categorized as follows:

- functional;
- environmental;

5.2.1. Functional loads

The functional loads applied to the submarine pipeline system are:

- pressure;
- temperature (thermal expansion and contraction);
- self-weight;
- adjacent structures;
- loads due to installation;
- residual loads;

5.2.2. Environmental loads

The environmental loads applied to the pipeline system are principally those arising from:

- hydrodynamic loads resulting from waves, winds and tidal currents
- soil;
- vibrations (vortex shedding);

5.3. Specific design requirements

In the design code NEN 3656, requirements for the design of submarine pipelines, risers and spools include following aspects:

- general checks on:
  - pressure containment;
  - static free span analysis;
  - stability during installation and operation;
  - collapse due to external hydrostatic pressure;
  - local buckling due to axial compressive forces and bending moments;
  - vibration due to vortex shedding;
  - fatigue;
- interaction between pipeline, spool piece and riser;
- loads by soils, including those resulting from elevated operating temperatures;
- buoyancy forces;
- environmental data;
- loads during installation and hydrotesting;
- upheaval buckling;
- accidental loads;

5.4. Load combinations

Three load conditions are considered for the detailed pipeline design:

- pipeline system in operating condition;
- pipeline system in hydrostatic test condition;
- pipeline system in installation condition;

For analyses of the pipeline system in operational condition, the following will be considered:

- functional loading:
  - weight of the pipeline and contents;
  - design pressure;
  - design temperature;
  - expansion due to pressure and temperature;

- environmental loading:
  - 100-years (all year) return period environmental data;

For analyses of the pipeline system under hydrostatic test condition, the following will be considered:

- functional loading:
  - weight of the pipeline and contents (= water);
  - hydrotest pressure;
  - installation temperature;
  - expansion due to hydrotest pressure;

- environmental loading:
  - 1-year (all year) return period environmental data;

For analyses of the pipeline system under installation condition (as installed), the following will be considered:

- functional loading:
  - weight of the pipeline (= flooded);
  - installation temperature;

- environmental loading:
  - 1-year (all year) return period environmental data;

A separate detailed analysis will be performed for the pipe-lay process by the pipeline installation contractor.

5.5. Assessment

With the prescribed loads, resulting stresses in the pipeline and spool pieces must be determined. The governing code NEN 3656 specifies a number of certain stresses that must be checked to allowable, code dependant, values.

For the pipeline an analytical approach will be used. The methods used in this analysis will be discussed in the next sections.

6. Design Criteria

6.1. Design Factors

The offshore pipeline system shall be designed to have sufficient strength to resist the loads and load combinations in all phases of its design lifetime.

NEN 3656 specifies design factors to use in the design of the pipeline, spools and risers.

After determination of the loads, these loads are multiplied by the relevant design factors, as given in Table 6.1, to obtain the design load:

Design load = design factor x load.

Loads	**Load factors for load combinations (a)**								
Load combinations	BC 1	BC 2	BC 3	BC 4	BC 5	BC 6	BC 7a	BC 7b	BC 8
Internal pressure (design pressure)	-	1.25	-	-	-	-	1.0		1.0
Internal pressure (In combination)	-	-	-	1.15	1.15	-	-	1.0	1.15
Internal pressure (max. Incidental pressure)	-	1.10	-	-	-	-	-		1.1
Temperature differences (c g)	1.0	-	1.10	1.10	-	-	1.0	1.0	-
Soil parameters (d)	-	-	(d)	(d)	(d)	-	-	Low	-
Forced deformation (e)	-	-	1.1	1.1	1.1	1.1	-		-
Own weight	1.1	-	1.1	1.1	1.1	1.1	1.0		1.0
(Possible) coating (h)	1.2	-	1.2	1.2	1.2	1.2	1.0	1.2	1.0
Pipe contents (h)	1.1	-	1.1	1.1	1.1	1.1	1.0	1.1	1.0
Installation loads (f)	1.1	-	-	-	-	1.1	-		-
Hydrostatic pressure	1.1	-	1.1	1.1	1.1	1.1	1.0	1.1	
Marine growth (h)	-	-	1.2	1.2	1.1	-	1.0	1.0	1.0
Hydrodynamic forces & platform movements	1.1	-	1.2	1.2	1.1	1.1	1.0	1.2	1.0

(a)	If a load has a favorable influence on the considered case this will not be considered if the load is variable and for a permanent load a multiplication factor of 0.9 is applied.
(b)	The maximum incidental pressure does not need to be checked separately however must be ascertained by the pressure control system.
(c)	During calculations of stress variations caused by temperature differences the highest and lowest occurring operation temperature should be considered. The displacements loads and moments exerting on connected equipment and/or structures are to be considered based on the design temperatures i.e. the temperature difference between the installation temperature and the maximum operational temperature.
(d)	Reference is made to ref. [1] – K.4 to determine load spreading factors
(e)	Forced deformations can be caused by: settling differences trench roughness execution sacking differences deformations due to prevented thermal expansion distortions in horizontal drilling and bottom-tow installation.
(f)	Examples of installation loads are those applied during pipelay tie-ins trenching landfalls and HDD etc.
(g)	Combined with measurements.
(h)	In the stability check (BC 7b) the most unfavorable combination must be chosen. If necessary divide by the relevant factor.

Table 6-1 Load factors (γ) according to NEN 3656

A description of the load combinations is shown below.

LC 1: Installation

LC 2: Only internal pressure, operating pressure, incidental pressure

LC 3: External load with zero internal pressure

LC 4: External load with internal pressure and temperature difference

LC 5: Variable load (primarily static load, e.g., temperature changes and pressure)

LC 6: External pressure, external load and internal pressure zero

LC 7: Incidental load (other than internal pressure)

LC 8: Dynamic loading

The stresses resulting from the combinations of load cases as defined above shall have to be compared with the limit stresses (see section 6.2.4).

Load combinations applicable for the design of the D12-B pipeline system shall be established and the limit states shall be assessed.

6.2. Stress-based Design

Stresses in the pipeline system can be calculated according to NEN 3656.

6.2.1. Hoop Stress

The hoop stress, σ_h, and the corresponding design stress S_h to be used for the equivalent stress calculation, are defined in NEN 3656 as:

$$\sigma_h = \frac{P_d \cdot (OD - t_{\min})}{2 \cdot t_{\min}}$$

and

$$S_h = \gamma_m \cdot \sigma_h$$

Where:

P_d	=	design pressure (N/mm^2)
t_{min}	=	minimum pipe wall thickness (mm)
OD	=	outside diameter of steel pipe (mm)
γ_m	=	material factor (1.1 for steel)

Further to this, NEN 3656 specifies additional requirements for bends with a bending radius R_b < 10 OD, to adjust the hoop stresses (torus effect):

$$S_h(bi) = \frac{2R_b - \frac{1}{2}OD}{2R_b - OD} \cdot S_h \quad \text{(for inside bend)}$$

$$S_h(bo) = \frac{2R_b + \frac{1}{2}OD}{2R_b + OD} \cdot S_h \quad \text{(for outside bend)}$$

6.2.2. Longitudinal stress

Longitudinal stress is calculated from the effects of:

- internal pressure;
- thermal expansion or contraction;
- curvature;

Furthermore, effects from self-weight and environmental loadings are taken into account.

The longitudinal stress calculation shall consider whether the pipeline is free to move or is partially- or fully restrained.

For a partially restrained pipeline, between the end of the pipeline and the virtual anchor length of the pipeline, the longitudinal stress, σ_l, and the corresponding design stress S_l is given by:

$$\sigma_l = \nu \cdot \sigma_h - \frac{F_f \cdot L_x}{A} \pm \sigma_b$$

$$S_l = \nu \cdot S_h - \gamma_{th} \cdot \frac{F_f \cdot L_x}{A} \pm S_b$$

Where:

$$F_f = f \cdot W_s$$

The value of F_f (N/m) is positive for a pipeline subject to expansion and negative for contraction.

$$\sigma_b = \frac{M \cdot OD}{2 \cdot I} \quad \text{and} \quad S_b = \gamma_b \cdot \sigma_b$$

Further:

ν	=	Poisson's ratio for elastic deformation (-) => 0.3
γ_{th}, γ_b	=	load factors (-)
F_f	=	longitudinal friction force between the pipe and seabed per unit length.
f	=	coefficient of friction between pipe and seabed (-)
W_s	=	submerged pipeline weight
L_x	=	distance from inlet to specified location (m)
A	=	cross-section area of steel (mm^2)
M	=	bending moment as a result of vertical and horizontal curvature (Nmm)
OD	=	outside diameter of steel pipe (mm)
I	=	moment of inertia of steel pipe (mm^4)

The bending moment is given by:

$$M = E \cdot I \cdot \sqrt{\frac{1}{R_{bh}^2} + \frac{1}{R_{bv}^2}}$$

Where:

E	=	Young's modulus of steel (MPa)
R_{bh}	=	horizontal bending radius (m)
R_{bv}	=	vertical bending radius (m)

For a fully restrained pipeline the longitudinal stress σ_l, and the corresponding S_l is:

$$\sigma_l = \nu \cdot \sigma_h - E \cdot \alpha \cdot \Delta T \pm \sigma_b$$

$$S_l = \nu \cdot S_h - \gamma_{th} \cdot E \cdot \alpha \cdot \Delta T \pm S_b$$

Where:

ν	=	Poisson's ratio for elastic deformation (-) => 0.3
α	=	coefficient of thermal expansion (m/m/°C)
ΔT	=	pipeline temperature difference at the considered location in the operational and installation phase of the pipeline

6.2.3. Tensile stress

Pipeline tension can occur because of an imposed tension during laying, a self-induced tension during trenching or a residual tension after lay barge installation.

The tensile stress, σ_t, and the corresponding S_t are calculated with:

$$\sigma_t = \frac{F}{A}$$

$$S_t = \gamma_t \cdot \sigma_t$$

Where:

F	=	applied tension force (N)
A	=	cross section area of steel (mm^2)
γ_t	=	load factor as given in Table 7-1 (-)

6.2.4. Limit state stress

After the determination, of respectively the axial and tangential stresses in relevant points along the circumference of pipeline cross sections with the heaviest load, these stresses shall be combined into an equivalent stress.

The Huber-Hencky / von Mises stress criterion is used to calculate the equivalent stress S_e:

$$S_e = \sqrt{S_h{}^2 + S_l{}^2 - S_h S_l + 3 \cdot \tau^2}$$

Where:

τ	=	Shear stress (N/mm^2)

The equivalent stress is checked in accordance with Table 6-2.

Load Combination	Equivalent stress for LC	Limit stress
LC 1	σ_v:pm	1.1 R_e / γ_m
LC 2	σ_p:pm	$R_{e(\Theta)}$ / γ_m
LC 3, (LC 3 + LC 2)	σ_v:pm	1.1 $R_{e(\Theta)}$ / γ_m
LC 3, LC 4	σ_v:pm	0.85 (R_e + $R_{e(\Theta)}$) / γ_m

Table 6-2 Limit stresses

Where:

R_e = specified minimum yield strength at 20ºC (N/mm^2)

$R_{e(\Theta)}$ = yield strength of the material at design temperature. For design

temperatures below or equal to 50ºC, $R_{e(\Theta)}$ is equal to Re, which is the specified minimum yield strength (SMYS) of the material at 20ºC (N/mm^2). For temperatures above 50ºC the value is found by linear interpolation between the yield strength at 20ºC and the yield strength at 100ºC / 150ºC

γ_m = material factor (1.1 for steel)

σ_v = equivalent stress (N/mm^2)

pm = primary membrane

7. Wall Thickness Analysis

7.1. General

The minimum required wall thickness of the pipelines is determined on the basis of criteria which are dictated in NEN 3656 (Ref. [1]) and which are described in Section 8 of the Basis of Design (Ref. [i]).

Authority requirements are given in Ref. [13].

Several phenomena are to be investigated prior to finalising the selected wall thickness. Elements to be taken into account:

- pressure containment;
- on-bottom stability;
- implosion;
- progressive plastic collapse;
- local buckling;
- bar buckling;

The following Sections present the methodology and results of the checks outlined above.

7.2. Pressure containment

7.2.1. Methodology

NEN 3656, states that for every load combination the design resistance (R_d) must be greater than or equal to the loading effect (S_d) or:

$$R_d \geq S_d$$

R_d is defined as: $R_d = R_{e(\Theta)} / \gamma_m$

Where:

$R_{e(\Theta)}$	=	yield strength of the material at design temperature (N/mm^2)
γ_m	=	material factor (1.1 for steel)

For load combination LC2 (internal pressure only), the equation for hoop stress can be expressed as:

$$\sigma_h = \frac{\gamma_p \cdot P_d \cdot (OD - t_{min})}{2 \cdot t_{min}}$$

Where:

σ_h	=	hoop stress (N/mm^2)
γ_p	=	load factor as per Table 5-3 (-) => 1.25
Pd	=	design pressure (N/mm^2)
OD	=	outside diameter of steel pipe (mm)
t_{min}	=	minimum wall thickness (mm)

The selected wall thickness (t_{nom}) is then determined by:

$$t_{nom} = \left\{ \frac{t_{\min} + CA}{1 - f_{tol}} \right\}$$

Where:

CA	=	applicable corrosion Allowance (mm)
f_{tol}	=	fabrication tolerance (%)

Further to this, NEN 3656 specifies additional requirements for bends with a bending radius R_b < 10 OD, to adjust the hoop stress of the inside and outside of the bend based on the hoop stress of the straight pipe (torus effect):

$$\sigma_h(bi) = \frac{2R_b - \frac{1}{2}OD}{2R_b - OD} \cdot \sigma_h \quad \text{(for inside bend)}$$

$$\sigma_h(bo) = \frac{2R_b + \frac{1}{2}OD}{2R_b + OD} \cdot \sigma_h \quad \text{(for outside bend)}$$

Where:

$\sigma_h(bi)$	=	Hoop stress at inside of the bend (N/mm2)
$\sigma_h(bo)$	=	Hoop stress at inside of the bend (N/mm2)
σ_h	=	Hoop stress straight pipe (N/mm2)
R_b	=	Bend radius (usually 5 OD)

7.2.2. Hydrostatic Testing

The hydrostatic testing of pipeline system has two objectives:

- verify the strength of the system
- verify that there are no leaks from the system

The test pressure, P_t, will be determined as per as per Section 10.18.3 of NEN 3656 (Ref. [1]).

$$P_{t.\min} = C_p \cdot P_d \cdot \frac{R_e}{R_{ev}}$$

Where:

C_p	=	pressure test coefficient (-) => 1.30 for gas lines; 1.25 for others
P_d	=	design operating pressure (N/mm^2)
R_e	=	minimum yield stress at 20 °C (N/mm^2)
R_{ev}	=	minimum yield stress at design temperature (N/mm^2)

The maximum hydrostatic test pressure is based on the weakest part of the pipeline/riser system to be tested. The pressure shall not exceed, $P_{t,max}$, which is defined by:

$$P_{t.\max} = \frac{2.R_e \cdot t_{\min}}{(OD - t_{\min})}$$

7.2.3. Results

The results of the wall thickness calculations detailed above are presented in Table 7-1. The results indicate that the required nominal wall thickness is 8.56 mm for straight pipe and 9.03 mm for 5D bends within the 500 m Zone. For pipeline sections outside the 500 m zone the required nominal wall thickness is 7.73 mm for straight sections of pipe. There are no 5D bends outside the 500 m Zone.

Considering these results, the next highest standard wall thickness of 12.7 mm has been selected. This covers all sections of the pipeline inside and outside of the 500 m Zone, including 5D bends.

Detailed calculations for inside and outside of the 500 m Zone are provided in Appendix A1 and A2.

Table 7-1: Wall Thickness Calculation Summary

Property	**10" gas line**	
	Within 500m Zone	**Outside 500 m Zone**
Input Data		
Material	L360NB	L360NB
Design temperature (°C)	65	65
Yield @ambient temperature (N/mm^2)	360	360
Yield @design temperature (N/mm^2)	343	343
Allowable Hoop stress (N/mm^2)	312	312
Outside diameter (mm)	273.1	273.1
Design pressure (barg)	148	148
Fabrication tolerance (%)	5.5	5.5
Corrosion allowance (mm)	3	3
Design factor (-)	1.3	1.3
Material Factor	1.1	1.1
Bend radius (mm)	1366	N/A
Results		
Minimum WT for pressure containment (mm)	8.56	7.73
Minimum bend WT for pressure containment (mm)	9.03	N/A
Nominal WT required for pressure containment (mm)	11.56	10.73
Nominal Bend WT for pressure containment (mm)	12.03	N/A
Selected WT (mm)	***12.7***	***12.7***
Hoop stress (N/mm^2)	296	267
Bend Hoop stress (N/mm^2)	313	N/A
Minimum hydrotest pressure (barg)	***202***	***202***

7.3. On-bottom Stability

7.3.1. Introduction

The aim of stability analysis is to verify that the submerged weight of the pipeline ensures lateral stability against environmental loading. On-bottom stability analysis is carried out for the following condition only:

- Installation – Flooded

The pipeline is to be laterally stable on the seabed for 1 year return period environmental conditions. Prior to hydrostatic testing and operation, the pipeline will be buried and therefore not subject any to environmental loading.

7.3.2. Hydrodynamic loads

Hydrodynamic loads arise from the relative motions between pipe and seawater. They consist of drag, lift and inertia forces.

The drag force F_D is given by:

$$F_D = C_D \cdot OD_{tot} \cdot \frac{1}{2} \cdot \rho \cdot V \cdot |V|$$

Where:

C_D	=	drag force coefficient (-)
OD_{tot}	=	total diameter of coated pipe (m)
ρ	=	mass density of surrounding fluid (kg/m^3)
V	=	velocity of the fluid normal to the pipe axis (m/s)

The lift force F_L is calculated by the following equation:

$$F_L = C_L \cdot OD_{tot} \cdot \frac{1}{2} \cdot \rho \cdot V^2$$

Where:

C_L	=	lift force coefficient (-)

The inertia force F_I is determined by the following equation:

$$F_I = \rho \cdot C_I \cdot \frac{\pi}{4} \cdot OD_{tot}^{\ 2} \cdot a$$

Where:

C_I	=	inertia force coefficient (-)
a	=	Fluid particle acceleration (m/s^2)

The recommended values of hydrodynamic coefficients for the on-bottom stability design as a function of the embedment of the pipeline are listed in Table 7-2.

Coefficient	Pipe embedment		
	0%	**10%**	**20%**
Drag	0.70	0.63	0.53
Lift	0.90	0.90	0.81
Inertia	3.29	2.80	2.30

Table 7-2 Overview hydrodynamic coefficients

The environmental data used for the on-bottom stability analysis is presented in Chapter4.3.2 The 1-year omni-directional significant wave height and current data will be considered.

The wave induced water particle velocities and accelerations will be determined using the appropriate wave theory for the design wave height, period and water depth. Phase shifts between horizontal and vertical water particle velocities will be considered.

7.3.3. Stability check

The stability of the pipelines is checked using the following relationship:

$$W_s > f_s \cdot \left(\frac{F_D + F_I}{f_w} + F_L \right) - \frac{F_P}{f_w}$$

Where:

W_s	=	pipeline submerged weight (N/m)
f_s	=	safety factor (-) => 1.1
F_D	=	drag force (N/m)
F_L	=	lift force (N/m)
f_w	=	friction factor (-)
F_I	=	inertia force (N/m)
F_P	=	passive soil resistance (N/m)

A safety factor (f_s) of 1.1 will be implemented. The above equation assumes absolute stability criteria. Note that the actual F_p is limited to the maximum of the combined drag and inertia forces.

The passive soil resistance is derived from:

$$F_p = 0.5 \cdot \rho_{soil} \cdot \varepsilon^2 \cdot K_p$$

Where:

ρ_{soil}	=	submerged soil density (kg/m^3)
ε	=	embedment of pipeline (m)
K_P	=	coefficient of passive soil resistance (-)

and K_P is calculated from :

$$K_P = \frac{1+\sin(\phi)}{1-\sin(\phi)} = \tan^2 \cdot \left(45 + \frac{\phi}{2}\right)$$

Where:

ϕ = angle of internal friction (°)

7.3.4. Results

Pipeline on-bottom stability analysis has been carried out using the methodology outlined in the above sub-sections.

The stability of the pipeline was checked for the installation flooded conditions considering 1-year omni-directional return period environmental loadings. The results of the analysis, giving the minimum required pipe weight for stability are summarised in Table 7-3. Detailed calculations can be found in Appendix B.

Table 7-3: On-bottom Stability Analysis – Results Summary

Property	Installation Flooded	
	Stability	Liquefaction
Pipe weight in air (kg/m)	133.1	133.1
Pipe content (kg/m)	49.4	49.4
Buoyancy (kg/m)	62.5	62.5
Available weight (kg/m)	70.6	133.1
Min. Required weight (kg/m)	58.4	91.2
CHECK	OK	OK

As can be seen from these results, lateral stability and sinking through the liquified soil during the period of time between installation and pipeline burial is ensured for a flooded pipe installation.

7.4. Buckling and Collapse

The following subsections present the checks for buckling and collapse of the pipe cross section as a results of external pressure, bending moments and axial forces. The checks are made for the different phases of installation, hydrotesting and operation considering the selected wall thickness of 12.7 mm. The methodology is presented in Sections 7.4.1 to 7.4.6 while results are presented in Section 7.4.7.

7.4.1. External overpressure

The collapse pressure P_c causing implosion (radial instability) due to an external overpressure can be determined using:

$$(P_c - P_e)\cdot(P_c{}^2 - P_p{}^2) = P_c \cdot P_e \cdot P_p \cdot 2 \cdot \delta_0 \cdot \frac{D_g}{t}$$

Where:

D_g	=	nominal diameter of pipe (mm) => ½·{OD_{nom} – (OD_{nom} – 2·t_{min})}
P_c	=	critical external pressure for collapse (N/mm2)
P_e	=	critical external pressure for elastic deformation (N/mm^2)
P_p	=	critical external pressure for plastic deformation (N/mm^2)
P_L	=	allowable external pressure (N/mm^2)
δ_0	=	initial deformation (mm)
t	=	nominal wall thickness (mm)

The critical external pressure P_p for plastic deformation is calculated from:

$$P_p = \frac{2 \cdot R_e \cdot t}{D_{nom}}$$

The critical external pressure P_e for elastic deformation is calculated from:

$$P_e = \frac{2 \cdot E}{1-\nu^2} \cdot \left(\frac{t}{D_{nom}}\right)^3$$

Where:

ν	=	Poisson's ratio for elastic deformation (-) => 0.3

As a part of this the initial deformation is derived from:

$$\delta_0 = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}}$$

Where:

D_{max}	=	largest diameter of the ovalized pipe cross section
D_{min}	=	smallest diameter of the ovalized pipe cross section

The maximum allowable external pressure is defined as:

$$\gamma_{g,p} \cdot P_L \leq \frac{\gamma_M \cdot P_c}{\gamma_{m,p}}$$

Where:

$\gamma_{g,p}$	=	load factor (-) => 1.05
γ_M	=	model factor (-) => 0.93
$\gamma_{m,p}$	=	material factor (-) => 1.45

7.4.2. Bending moment

In case of a bending moment on the pipe, the moment which will cause buckling is calculated from the plastic moment of the pipe section.

$$M_c = D_{nom}{}^2 \cdot t \cdot R_e$$

The maximum allowable bending moment, accounting for the various design factors, is defined as:

$$\gamma_{g,M} \cdot M_L \leq \frac{\gamma_M \cdot M_c}{\gamma_{m,M}}$$

Where:

$\gamma_{g,M}$	=	load factor (-) => 1.1
γ_M	=	model factor (-) => 1.0
$\gamma_{m,M}$	=	material factor (-) => 1.3
M_L	=	allowable bending moment for buckling (Nm)
M_c	=	critical bending moment for buckling (Nm)

7.4.3. Combined external pressure and bending moment

When external pressure exists in combination with a bending moment besides the checks above the condition for combined stresses as shown below shall be fulfilled.

$$\frac{\gamma_{g,p} \cdot P_L}{P_c / \gamma_{m,p}} + \left(\frac{\gamma_{g,m} \cdot M_L}{M_c / \gamma_{m,M}} \right)^n \leq \gamma_M$$

Where:

$$n = 1 + 300 \cdot \frac{t}{D_{nom}}$$

Where:

$\gamma_{g,p}$	=	load factor for pressure (-) => 1.05
$\gamma_{g,m}$	=	load factor for bending (-) => 1.55
γ_M	=	model factor (-) => 0.93
$\gamma_{m,p}$	=	material factor for pressure (-) => 1.25
$\gamma_{m,M}$	=	material factor for bending (-) =>1.15
M_L	=	allowable bending moment for buckling (Nm)
M_c	=	critical bending moment for buckling (Nm)

7.4.4. Progressive plastic collapse

Progressive plastic deformation load cycle will lead to extreme deformation, collapse and cracks initiation through the wall.

The condition for avoiding buckle propagation is:

$$\varepsilon_{\max} = \alpha \cdot \Delta T \leq \left[\frac{R_{ev}}{E} \cdot \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_h}{R_{ev}}\right)^2} + \frac{R_e}{E}\sqrt{0.9 - \frac{3}{4}\left(\frac{\sigma_h}{R_e}\right)^2} \right]$$

Where:

α	=	coefficient of linear thermal expansion (m/ m/ ° C)
ΔT	=	temperature differential [° C] (design – installation)

Parameters have to be factored as defined in section 6.

7.4.5. Local buckling

In accordance with NEN 3656, if OD / t < 55, an assessment on local buckling can generally be omitted. For this project the OD / t ratio is 273.1 / 12.7 = 21.5, which is well below 55; hence local buckling will not be investigated further.

7.4.6. Bar buckling

In a free span the pipeline will be susceptible to bar buckling. Bar buckling may occur due to an effective axial compressive force (N) in the pipeline arising from internal pressure and temperature. The axial force (compression negative) in an axially restrained pipeline is based on the longitudinal stress:

$$N = A \cdot (\nu \cdot S_h - \gamma_t \cdot E \cdot \alpha \cdot \Delta T)$$

Where:

A	=	cross sectional area of steel (mm^2)
ν	=	Poisson's ratio for elastic deformation (-) => 0.3
S_h	=	factored hoop stress (N/mm^2)
γ_t	=	load factor as given in Table 5-3 (-)
α	=	coefficient of thermal expansion (m/m/°C)
ΔT	=	pipeline temperature differential (° C) (design – installation)

The factored hoop stress (S_h) is calculated from:

$$S_h = \gamma_P \cdot \sigma_h$$

and

$$\sigma_h = \frac{P_d \cdot (OD - t_{\min})}{2 \cdot t_{\min}}$$

Where:

P_d	=	design pressure (N/mm^2)
t_{min}	=	minimum pipe wall thickness (mm)
OD	=	outside diameter of steel pipe (mm)
γ_P	=	load factor as given in Table 5-3 (-)

The buckling length is based on the Euler buckling load definition, defined in Ref. [3]. Bar buckling is avoided if the span length fulfils:

$$L \leq \sqrt{4 \cdot \pi^2 \frac{E \cdot I}{|N|}}$$

Where:

L	=	allowable span length (mm)
I	=	moment of inertia (mm^4)

7.4.7. Results

Results of the various buckling and collapse checks as described above in the above sections are reported in Tables 7-4, 7-5 and 7-6 for the installation, hydrotest, and operational load cases respectively. The checks indicate that the selected wall thickness of 12.7 mm is sufficient to prevent implosion and progressive plastic collapse from an external overpressure. Maximum static span lengths, to prevent buckling and collapse have been determined as 39.1 m, 37.6 m and 28.2 m for the installation, hydrotest and operational load cases respectively. Note however that the dynamic spans assessed in Section 8.2.4 are below these values and hence are governing. Detailed calculations for these checks can be found in Appendix A3, A4 and A5.

Table 7-4: Buckling and Collapse Results Summary – Installation Flooded Load Case

Property	10" gas line
Collapse - external pressure only	
Actual external pressure (N/mm^2)	0.51
Implosion pipe collapse pressure (N/mm^2)	19.8
Implosion check	**OK**
Collapse – bending moment only	
Maximum allowable bending moment (Nm)	2.23 E5
Collapse – external pressure & bending moment only	
Maximum allowable bending moment (Nm)	1.57 E5
Maximum allowable collapse span length (m)	**39.1**
Progressive plastic collapse	
Actual strain (-)	0.0001
Allowable strain (-)	0.0033
Progressive collapse check	**OK**
Local buckling	
OD/t ratio	20.8
Allowable ratio	55
Local buckling check	**OK**
Bar buckling	
Maximum allowable bar buckling span length (m)	**49.7**

Table 7-5: Buckling and Collapse Results Summary – Hydrotest Load Case

Property	10” gas line
Collapse - external pressure only	
Actual external pressure (N/mm^2)	0.51
Implosion pipe collapse pressure (N/mm^2)	19.8
Implosion check	**OK**
Collapse – bending moment only	
Maximum allowable bending moment (Nm)	2.23 E5
Collapse – external pressure & bending moment only	
Maximum allowable bending moment (Nm)	1.57 E5
Maximum allowable collapse span length (m)	**37.6**
Progressive plastic collapse	
Actual strain (-)	0.0001
Allowable strain (-)	0.0023
Progressive collapse check	**OK**
Local buckling	
OD/t ratio	20.8
Allowable ratio	55
Local buckling check	**OK**
Bar buckling	
Maximum allowable bar buckling span length (m)	**No compressive force**

Table 7-6: Buckling and Collapse Results Summary – Operation Load Case

Property	10" gas line
Collapse - external pressure only	
Actual external pressure (N/mm^2)	0.51
Implosion pipe collapse pressure (N/mm^2)	19.8
Implosion check	**OK**
Collapse – bending moment only	
Maximum allowable bending moment (Nm)	2.23 E5
Collapse – external pressure & bending moment only	
Maximum allowable bending moment (Nm)	1.57 E5
Maximum allowable collapse span length (m)	**29.4**
Progressive plastic collapse	
Actual strain (-)	0.0007
Allowable strain (-)	0.0027
Progressive collapse check	**OK**
Local buckling	
OD/t ratio	20.8
Allowable ratio	55
Local buckling check	**OK**
Bar buckling	
Maximum allowable bar buckling span length (m)	**28.2**

8. Free Span analysis

8.1. Introduction

Combining hoop, longitudinal and bending stresses in the pipeline, which shall satisfy criteria for equivalent stresses, gives the maximum allowable static span lengths. Checks are to be made for the installation, hydro test and operational load

Spanning of a pipeline on the seabed causes forces and stresses in the pipe. The criterion for accepting a pipeline configuration is that the pipe should not be subjected to over-stressing, nor to excessive dynamic loading because of resonant oscillations of the pipe caused by the vortex shedding phenomenon during installation, testing and throughout its operating life.

The pipeline span assessment includes the following items:

- Static span analysis
- Dynamic span analysis.

The static analysis concerns the determination of the pipe stresses under functional- and static environmental loads for a given span length.

The dynamic span analysis is based on criteria for prevention of vortex induced vibrations (VIV) as outlined in NEN 3656 considering both current- and wave induced velocities.

In addition, operational limits of the trenching equipment, limits the span gap (distance between the pipe and the seabed).

Although the pipeline will be buried below the seabed prior to its operation, the pipeline must be checked for spanning for the period between installation and burial.

In the analysis, along with the seabed topography, both functional and environmental loads are taken into consideration to check pipeline structural integrity under the considered load cases.

8.2. Static span

Combining hoop, longitudinal and bending stresses in the pipeline, which shall satisfy criteria for equivalent stresses, gives the maximum allowable static span lengths. Checks are to be made for the installation, hydro test and operational load case.

The maximum bending moment is calculated from the (vector) combination of the pipelines' own weight and hydrodynamic forces for the maximum wave condition:

$$q = \sqrt{\gamma_W{}^2 \cdot W_S{}^2 + \gamma_H{}^2 \cdot (F_D + F_I)^2}$$

Where:

γ_W	=	load factor as per Table 6-1 (-)
γ_H	=	load factor as per Table 6-1 (-)

End fixity of an actual span is commonly assumed between fixed - fixed and fixed – pinned and the bending moment (M) calculated from:

$$M = \frac{q \cdot L^2}{10}$$

Where:

L	=	Maximum allowable span length [m]

The maximum allowable bending moment (M_{all}) is given by:

$$M_{all} = \frac{2 \cdot I \cdot \sigma_b}{OD}$$

Where:

I	=	moment of inertia (m^4)
OD	=	pipeline outside diameter (m)
s_b	=	maximum allowable bending stress

The maximum allowable static span can then be determined by:

$$L\max = \sqrt{\frac{20 \cdot \sigma_b \cdot I}{OD \cdot q}}$$

The maximum allowable span length follows from the condition that the equivalent stress (S_e) from the load combination satisfies the following conditions:

For the operational and hydrotest cases:

$$S_e \leq 0.85 \times (R_e + R_{ev}) / \gamma_m$$

For the installation case:

$$S_e \leq R_e / \gamma_m$$

Where:

R_e	=	minimum yield stress at 20 °C (N/mm^2)
R_{ev}	=	minimum yield stress at design temperature (N/mm^2)
γ_m	=	material factor (-) => 1.1

8.2.1. Load cases

The maximum static span will be determined for the load cases, and considering the environmental load return periods, as detailed in Table 8-1:

Condition	Wave Height Return Period	Current velocity Return Period
Installation	$H_{max,1yr}$	1 yr
Hydrotest	$H_{max,1yr}$	1 yr
Operational,1	$H_{max,100yr}$	10 yr
Operational,2	$H_{max,10yr}$	100 yr

Table 8-1 Load Cases for Span Assessment

8.2.2. Results

Table 8-2 to 8-5 present the maximum allowable spans for the pipeline for the different load cases (waves and current coming from the West at a water depth of 28.6m LAT) assessed and listed in Table 7-1. Detailed calculation sheets can be found in Appendix C.

Table 8-2: Allowable Static Span Length – Installation Flooded Condition

Property	Unrestrained pipe		Restrained pipe	
	Tension	Compression	Tension	Compression
Hoop stress (N/mm^2)	4.6	4.6	4.6	4.6
Max. longitudinal stress (N/mm^2)	329.6	-324.9	329.6	-324.9
Longitudinal hoop stress (N/mm^2)	2.0	2.0	1.4	1.4
Thermal expansion stress (N/mm^2)	N/A	N/A	-12.2	-12.2
Max. allowable bending stress (N/mm^2)	327.3	-327.0	327.3	-314.1
Maximum allowable span (m)	**46.2**	**46.2**	**46.2**	**45.3**

Table 8-3: Allowable Static Span Length – Hydrotest Condition

Property	Unrestrained pipe		Restrained pipe	
	Tension	Compression	Tension	Compression
Hoop stress (N/mm^2)	336.2	336.2	336.2	336.2
Max. longitudinal stress (N/mm^2)	642.2	-306.0	642.2	-306.0
Longitudinal hoop stress (N/mm^2)	103.1	103.1	100.8	100.8
Thermal expansion stress (N/mm^2)	N/A	N/A	-13.4	-13.4
Max. allowable bending stress (N/mm^2)	539.1	-409.1	554.7	-393.5
Maximum allowable span (m)	**58.3**	**50.7**	**59.1**	**49.8**

Table 8-4: Allowable Static Span Length – Operational Condition – Load Case 1 (LC1): $H_{max,100yr}$ & $U_{cur,10yr}$

Property	Unrestrained pipe		Restrained pipe	
	Tension	Compression	Tension	Compression
Hoop stress (N/mm^2)	245.1	245.1	245.1	245.1
Max. longitudinal stress (N/mm^2)	622.8	-377.7	622.8	-377.7
Longitudinal hoop stress (N/mm^2)	75.5	75.5	73.5	73.5
Thermal expansion stress (N/mm^2)	N/A	N/A	-147.4	-147.4
Max. allowable bending stress (N/mm^2)	543.4	-453.2	543.4	-303.8
Maximum allowable span (m)	**44.2**	**40.3**	**44.2**	**33.0**

Table 8-5: Allowable Static Span Length – Operational Condition – Load Case 2 (LC2) : $H_{max,10yr}$ & $U_{cur,100yr}$

Property	Unrestrained pipe		Restrained pipe	
	Tension	Compression	Tension	Compression
Hoop stress (N/mm^2)	245.1	245.1	245.1	245.1
Max. longitudinal stress (N/mm^2)	622.8	-377.7	622.8	-377.7
Longitudinal hoop stress (N/mm^2)	75.5	75.5	73.5	73.5
Thermal expansion stress (N/mm^2)	N/A	N/A	-147.4	-147.4
Max. allowable bending stress (N/mm^2)	543.4	-453.2	543.4	-303.8
Maximum allowable span (m)	**53.4**	**48.8**	**53.4**	**39.9**

8.3. Dynamic span

8.3.1. Introduction

Flow of water particles induced by currents and waves perpendicular to a spanning pipeline or riser span can lead to vortices being shed. This will disrupt the flow around the pipe and thereby potentially cause periodic loads on the pipeline or riser, also known as Vortex Induced Vibration (VIV).

The natural frequency of a span being close to the vortex shedding frequency can result in a resonant oscillation, possibly resulting in fatigue failure of the pipeline or riser.

The oscillations of the span may occur in two directions:

- in line with the flow (parallel to the flow direction of the water particles)
- in cross flow direction (perpendicular to the flow direction of the water particles)

When assessing VIV, the span should be confirmed to be within acceptable limits set by either avoidance of VIV or an acceptable fatigue life for both the installation and operational condition.

Relevant dimensionless parameters governing the VIV phenomenon are the reduced velocity (V_r) and stability parameter (K_s).

The reduced velocity (V_r) parameter is defined by:

$$V_r = \frac{V_s}{f_{n \cdot OD_{tot}}}$$

Where,

V_s	=	water particle velocity due to current and significant wave (m/s)
f_n	=	1st natural frequency of the pipe span (1/s)
OD_{tot}		total outside diameter of the pipe (m)

The 1st natural frequency can be calculated from:

$$f_n = \frac{a}{2\pi} \cdot \sqrt{\frac{E \cdot I}{m_e \cdot L^4}}$$

Where,

a	=	frequency factor (-) => 15.4 for a fixed-pinned beam, which is used for the pipe
E	=	Young's modulus (N/m^2)
I	=	moment of inertia (m^4)
L	=	length of span in pipeline / riser (m)

The stability parameter (K_s) is defined by:

$$K_s = \frac{2 \cdot m_e \cdot \delta}{\rho_{sw} \cdot OD_{tot}^2}$$

Where,

m_e	=	effective mass of pipe (kg/m)
ρ_{sw}	=	density seawater (kg/m^3)
δ	=	logarithmic decrement of damping (-) => δ = 0.126 for steel

The effective mass of the pipe can be calculated as:

$$m_e = m + \pi/4 \cdot C_M \cdot \rho_{sw} \cdot OD_{tot}{}^2$$

Where,

m	=	Pipeline / riser mass (kg/m)
Cm	=	added mass coefficient (-)

NEN 3656 states that In-line oscillations will occur if $K_s \leq 1.8$ and cross flow oscillations will occur if $K_s \leq 16$.

8.3.2. In-line VIV

NEN 3656 furthermore states that in-line oscillations of the span occur if the reduced velocity is within the range of: $1.0 \leq Vr \leq 3.5$

Vortices around a spanning pipe occur in a relatively steady state environment. The wave induced velocity varies from a maximum at t=0, to zero at $t=1/4*T_{wave}$. Furthermore, the system does not respond instantaneously to the applied forcing. To ignore the wave induced velocity in assessing the allowable dynamic span length would be too optimistic, to account for the maximum induced value would be too conservative, therefore reference is made to DNV-RP-F105. “Free Spanning Pipelines.” (ref. [3]).

According to Ref. [3], fatigue damage due to in-line VIV can be neglected if the current flow velocity ratio α, as defined by the equation below is smaller than 0.8.

$$\alpha = \frac{v_{cur}}{v_{cur} + v_{wave}}$$

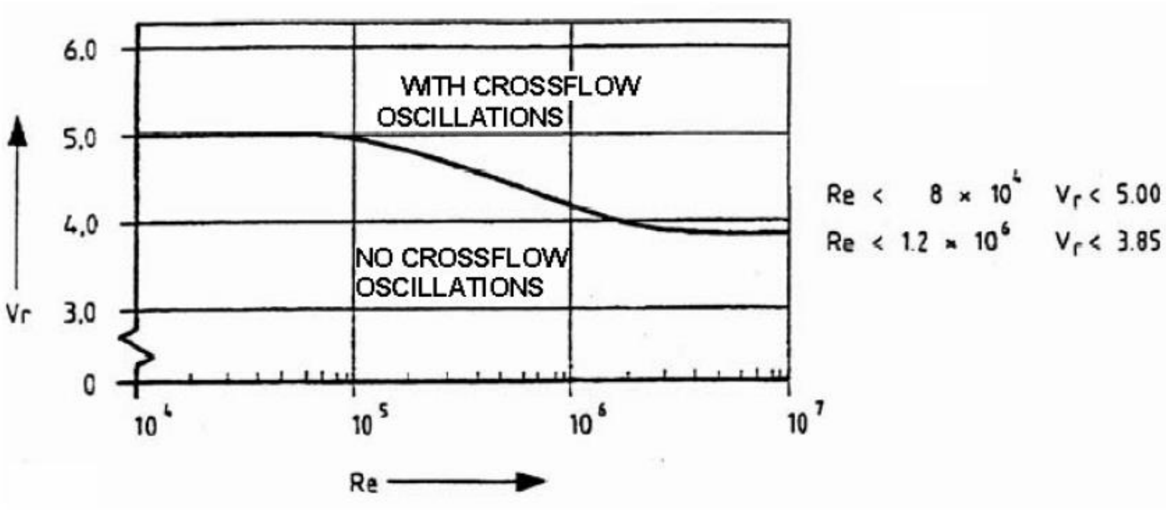
Where,

v_{cur}	=	Particle velocity due to current [m/s]
v_{wave}	=	Particle velocity due to waves [m/s]

8.3.3. Cross-flow VIV

The occurrence of cross flow oscillations depends on the magnitude of the Reynolds number, Re, and the reduced velocity as given in Figure 8-1.

Figure 8-1 Reduced velocity for cross flow oscillations



$$\mathrm{Re} = \frac{\mathrm{v} \cdot OD_{tot}}{\nu}$$

Where,

v	=	particle velocity (m/s)
OD_{tot}	=	pipeline outside diameter (m)
ν	=	Kinematic viscosity water (m^2/s) => 1,307 x 10^{-6} (@10 °C)

8.3.4. Results

The maximum allowable dynamic spans have been determined using the methodology above and considering the design load cases as listed in Table 8-1.

The results are presented in Table 8-6 and 8-7 for the inline and cross-flow VIV assessments respectively.

Table 8-6: In-line VIV Summary

Property	Installation	Hydrotest	LC 1 Operation	LC 2 Operation
Effective mass, m_e (kg/m)	208.2	208.2	163.1	163.1
Stability parameter, K_s (-)	0.66	0.66	0.51	0.51
Limit reduced velocity, Vr (-)	1.0	1.0	1.0	1.0
Wave hor. particle velocity, u_{wh} (m/s)	0.80	0.80	1.60	1.21
Current hor. particle velocity, $u_{cm,perp}$ (m/s)	0.27	0.27	0.29	0.31
Outer P/L dimeter, D_o (mm)	278.7	278.7	278.7	278.7
Limit span frequency, f_1 (1/s)	3.84	3.84	6.77	5.46
Allowable span length ($L_{span,in}$) (m)	**13.8**	**13.8**	**11.0**	**12.3**

Table 8-7: Cross-flow VIV Summary

Property			LC 1	LC 2
	Installation	Hydrotest	Operation	Operation
Wave hor. particle velocity, u_{wh} (m/s)	0.80	0.80	1.60	1.21
Current hor. particle velocity, $u_{cm,perp}$ (m/s)	0.27	0.27	0.29	0.31
Pipe Outside, D (mm)	278.7	278.7	278.7	278.7
Reynolds nr. (-)	5.97 E5	5.97 E5	1.05 E6	8.51 E5
Critical reduced velocity, Vr (-)	4.38	4.38	4.20	4.27
Span frequency, f_1 (1/s)	0.88	0.88	1.61	1.28
Allowable span length ($L_{span,cross}$) (m)	**28.9**	**28.9**	**22.7**	**25.4**

9. Bottom roughness

9.1. Methodology

To ensure the structural integrity of the pipeline over the entire design life finite element analyses are carried out using the industry proven ANSYS finite element software.

The analysis will assess the interaction between the pipeline and the supporting soil along the entire pipeline route and will be carried out in accordance with the requirements of NEN 3656 (Ref. [1]). In addition, the length, number, and configuration of pipeline spans can be determined. The analysis will also check that the proposed burial depth of 0.8m to top of pipe (TOP), is sufficient to suppress upheaval buckling.

The analysis will account for the load history of the pipelines over the design life by considering the following four load cases:

- Installation (flooded);
- Hydrostatic testing;
- Pipeline operation - nominal (nominal wall thickness, content filling, maximum operating pressure and temperature);
- Pipeline operation – corroded (corroded wall thickness, content filling, maximum operating pressure and temperature).

The following Table presents the design loads that will be considered in the analysis, based on the four load cases.

Table 9-1: Overview design loads

Load	Installation	Hydrotest	Operation
Pressure	N/A	Hydrotest Pressure	Design Pressure
Temperature	Seawater Temperature	Seawater Temperature	Design Temperature
Internal Fluid	Seawater	Seawater	Product Filled
Wall Thickness	Nominal	Nominal	Nominal /Fully corroded

All loads shall be factored as per the requirements of NEN 3656 (Ref. [1]). The applicable load factors to be applied are given in Section 6.1.

To ensure the structural integrity of the pipeline, over the projected design life, three acceptance criteria have been identified:

1. Allowable equivalent stress;
2. Allowable free spans length;
3. Allowable span gap (trenching requirement).

If the pipeline fails any of the criteria described above some form of mitigation measure is required. Allowable stresses, as per NEN 3656 (Ref. [1]) for various load combinations are given in Table 9-2. The allowable free span lengths were determined in the pipeline free span analysis and are presented in Table 8-6. Note the maximum allowable span length is 11 m.

Table 9-2: Allowable Stresses

Case	Load Combination As Per NEN3650 Table 2.	Limit Stress	Allowable Equivalent Stress
Installation	LC1	$R_{e(\theta)} / \gamma_m$	327 MPa
Hydrotest	LC1	$R_{e(\theta)} / \gamma_m$	327 MPa
Operation (Nominal / Corroded)	LC4	$0.85 (R_e + R_{e(\theta)}) / \gamma_m$	543 MPa

Where:

Re = specified minimum yield strength at 20ºC (N/mm^2).

$R_{e(\theta)}$ = the yield strength of the material at design temperature.

γ_m = material factor (for steel 1.1).

The pipeline span gap height (i.e. the distance between bottom of pipe and the seabed) is limited by the ability of the trenching equipment to traverse such gaps. As the trenching equipment is not know at this stage in the project the span gap height is limited to a maximum value of 0.5 m.

The following subsections describe in detail the finite element model which shall be used to conduct the bottom roughness analysis.

9.2. Finite Element Model

The pipeline is modelled using ANSYS's dedicated submerged pipe element "PIPE59". This element is a uniaxial element with tension-compression, torsion, and bending capabilities and can account for internal pressure effects. The element is a 3D element with six degrees of freedom, translations in the x, y and z directions and rotations about the x, y and z axes. In addition, the element accounts for buoyancy, wave and current loads, and is capable of large deflections and rotations.

The pipeline is modelled with a maximum element length of 0.5 m and accounts for all curvatures in the horizontal plane and undulations in the vertical plane. Pipe-soil interaction is simulated using three independent non-linear spring elements (COMBIN39) attached to each pipe element. The springs represent the soil frictional resistance in the axial and lateral directions and the soils bearing capacity in the vertical direction.

As the pipeline will be buried after the installation phase, additional non-linear springs representing the uplift resistance of the trenched backfill material, are also attached to the pipe elements. A detailed description of how the pipe soil interaction will be modelled is provided separately in Section 9.4.

Seabed roughness is simulated by displacing the vertical soil spring nodes to the correct depth based on the bathymetric data and allowing the pipe to move and rest on the vertical springs connected between pipe and soil nodes.

At pipeline termination points an additional axial spring is attached to the pipeline ends to incorporate the structural response of the subsea tie-in spool/riser and supporting piping.

9.3. Pipeline Configuration and Loading Sequence

The finite element model extends from the target box at the D12-B platform (KP 0.000) to taget box at the D15-FA-1 platform (KP 11.815).

For the installation load cases the pipeline is considered on the surface of the seabed, for the hydrotest and operational cases the pipeline is considered buried to a depth of 0.8 m TOP. A trench transition length of 50m is considered at both pipeline ends.

The ground profile considered for the various load cases can be seen in Figure 9-1.

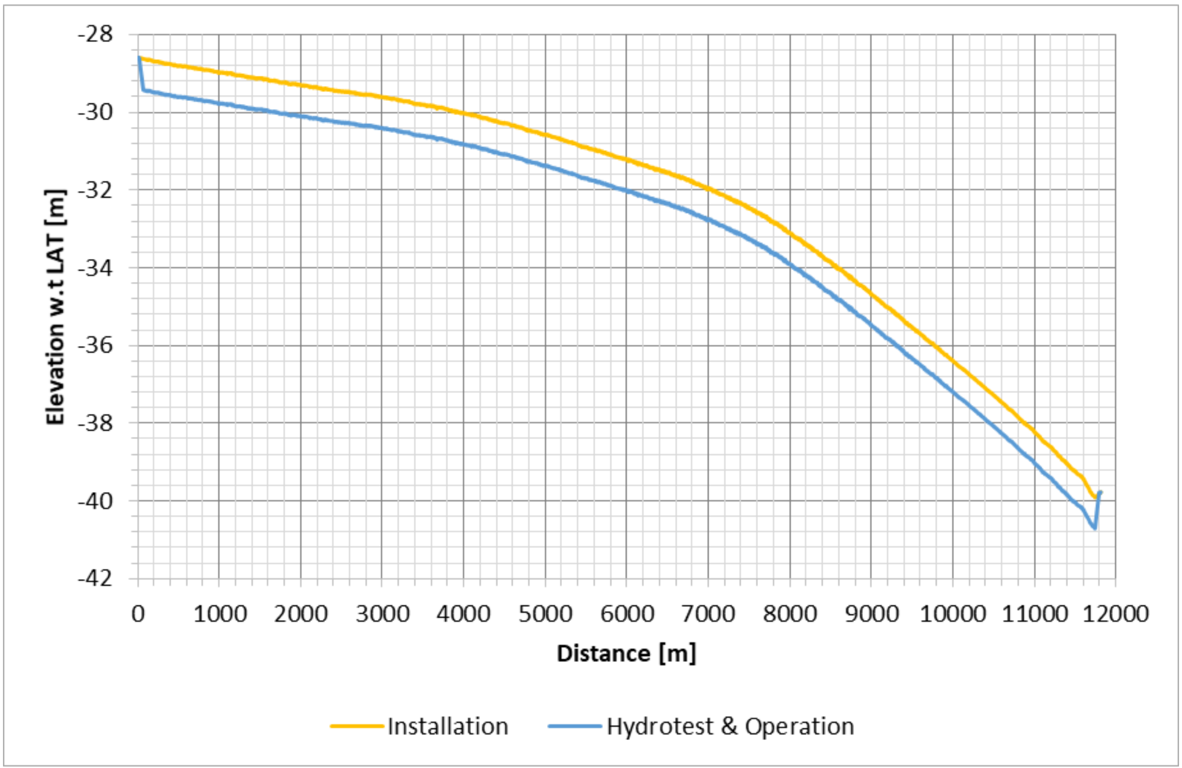


Figure 9-1: Pipeline Ground Profiles

The loading sequence applied aims to mimic as closely as possible the loading history of the pipeline through its different stages of operation. The loading sequence shall be as follows:

1. Initially the pipeline will be modelled flooded, straight in the lateral plane, flat in the vertical plane and accelerations due to gravity are applied;
2. The vertical springs are then displaced to their correct depth based on the bathymetric data. The pipe is then allowed to displace resting on these springs, thereby taking a natural shape and simulating the pipes configuration after pipe installation;
3. After installation, the vertical springs are further displaced to the depth based on the assumed buried pipe profile. See Figure 9-1.
4. The pipeline hydro-test pressure is applied, after which the pipeline is emptied and depressurized simulating the system hydrotest;
5. The pipeline is the then refilled with the operating fluid contents;
6. The design pressure and design temperature are then applied as body and surface loads on the elements simulating the pipelines under design conditions.

Pipeline free spans and stresses are extracted for each load cases and compared to the design criteria.

9.4. Pipe-soil interaction

The characteristics of the springs, which simulated the pipe-soil interaction, are defined through non-linear force-deflection curves. The force-deflection curves describe the frictional restraint provided by the soil to the pipeline in the axial and lateral direction and the soil's bearing capacity / upwards resistance in the vertical direction. The upcoming sections describe how the force-deflection curves of the springs are generated. The considered geotechnical parameters of the seabed soil are given Table 4-12.

9.4.1. Exposed pipeline – axial soil resistance

The axial soil resistance for a pipeline / spool piece resting on the seabed, per meter pipe-length, is a function of the pipe submerged weight (vertical load) and the axial Coulomb friction coefficient. The axial friction is determined as follows:

$$F_{axial} = \mu_{Coulomb} w_s$$

Where:

- F_{axial} = Peak axial soil resistance [N/m]
- $\mu_{Coulomb}$ = Coulomb friction coefficient [-]
- w_s = Pipe submerged weight [N/m]

The axial restraint will be described through a bi-linear force-displacement relationship, as shown in Figure 9-2. The stiffness of the springs varies along the pipeline route and between load steps to account for variations in the pipe submerged weight and soil conditions.

The axial spring mobilization displacement is assumed to be 1mm.

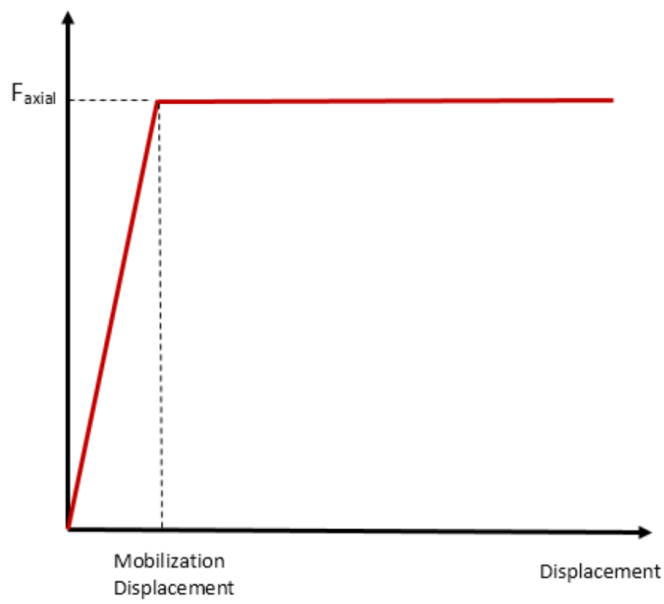


Figure 9-2 Axial resistance Force-Displacement curve

9.4.2. Exposed pipeline – lateral soil resistance

Lateral soil resistance is composed of two parts:

- Coulomb friction.
- Passive soil resistance due to the build-up of soil penetration (and hence a soil berm, as the pipe moves laterally).

To account for both components of resistance, an equivalent friction coefficient shall be used, which is defined as:

$$\mu_{equivalent} = \mu_{Coulomb} + \mu_{passive}$$

Where:

- μ_{eqv} = Equivalent lateral friction coefficient [-]
- $\mu_{Coulomb}$ = Coulomb friction coefficient [-]
- $\mu_{passive}$ = Passive soil resistance coefficient [-]

The passive soil resistance model proposed in DNV's Recommended Practice, DNV-RP-F109 (Ref. [5]) will be used.

The passive soil resistance coefficient, for a pipeline resting on a sandy seabed, depends on the pipe penetration depth into the soil and can be determined by the formulation:

- $\mu_{passive} = \frac{F_R}{F_C} = (5\kappa_s - 0.15\kappa_s{}^2)\left(\frac{z_p}{D}\right)^{1.25}$ if $\kappa_s \leq 26.7$
- $\mu_{passive} = \frac{F_R}{F_C} = \kappa_s\left(\frac{z_p}{D}\right)^{1.25}$ if $\kappa_s > 26.7$

Where:

- F_R = Passive resistance force [N/m]
- F_C = Vertical contact force between pipe and soil [N/m]
- D = Pipe outside diameter, including all coatings [m]
- z_p = Total pipe penetration [m]
- κ_s = Soil parameter for sandy soils [-]
- γ'_s = Submerged unit soil weight [N/m^3]

The soil parameter for sand, κ_s, is determined as:

$$\kappa_s = \frac{\gamma'_s D^2}{F_C}$$

The total pipe penetration is taken as the sum of:

- Initial penetration due to self-weight.
- Penetration due to dynamics during laying.
- Penetration due to pipe movement under the action of waves and current.

The pipe static/initial penetration due to self-weight for pipelines resting on sandy soil will be determined using the following formula taken from DNV-RP-F109 [5]:

$$\frac{z_{pi}}{D} = 0.037\kappa_s{}^{-0.67}$$

Just as for the axial restraint, the lateral soil resistance will be described through a bi-linear force-displacement relationship as presented in Figure 9-2. The friction forces are increased monotonically to a maximum value calculated as the product of the pipe submerged weight (w_s) and the equivalent friction coefficient (μ_{eqv}), at a mobilisation distance of 1mm.

9.4.3. Vertical soil bearing capacity (Downward resistance)

The static vertical soil reaction per unit length can be determined based on bearing capacity formulas for ideal 2-D strip foundations, as per DNV-RP-F105 [3]:

$$R_V = \gamma_{soil} N_q v_{eff} + 0.5 N_\gamma B$$

Where:

- R_V = Vertical soil reaction [N/m]
- N_q & N_γ = Bearing capacity factors [-]
- v_{eff} = Effective penetration [m] (The larger of $v - D/4$ and 0)
- v = Vertical penetration [m]
- B = Contact width for pipe-soil load transfer [m]

The bearing capacity factors are determined as follows:

$$N_q = e^{\pi \tan\varphi_s} \tan^2\left(45 + \frac{\varphi_s}{2}\right)$$

Where:

φ_s = Angle of internal friction [°]

$N_\gamma = 1.5\left(N_q - 1\right)\tan\varphi_s$

The contact width for pipe-soil load transfer, B, is given by:

- $B = 2\sqrt{(D-v)v}$ if $v \leq D/2$
- $B = D$ if $v > D/2$

9.4.4. Buried pipeline – axial soil resistance

Soil resistance forces for buried pipeline sections are based on ASCE's "Guidelines for the Design of Buried Steel Pipe" [9].

The maximum axial soil force that can be transmitted to the pipe per unit length is given by:

$$T_u = \pi D \alpha c + \pi D H \gamma'_s \frac{1 + K_0}{2} \tan\delta$$

Where:

- c = Soil cohesion representative of soil backfill material [N/m^2] (c=0 for sand)
- H = Depth to the pipeline centreline [m]
- K_0 = Coefficient of earth pressure at rest [-] $(1 - \sin\varphi_s)$
- α = Adhesion factor [-]
- δ = Interface angle of friction for pipe and soil [°] $(f\varphi_s)$
- f = Coating dependent factor relating the internal friction angle of the soil to the friction angle at the pipe soil interface.

The axial resistance mobilisation displacement, Δ_t, is determined considering the soil type as follows:

- Δ_t = 3mm for dense sand
- Δ_t = 5mm for loose sand
- Δ_t = 8mm for stiff clay
- Δ_t = 10mm for soft sand

9.4.5. Buried pipeline – lateral soil resistance

The maximum lateral force that the soil can transmit per unit pipe length is given by:

$$P_u = N_{ch}cD + N_{qh}\gamma'_s HD$$

Where:

- N_{ch} = Horizontal bearing capacity for clay (0 for c=0).
- N_{qh} = Horizontal bearing capacity factor for sand (0 for $\varphi_s = 0$)

The bearing capacity factors are taken from the following figure.

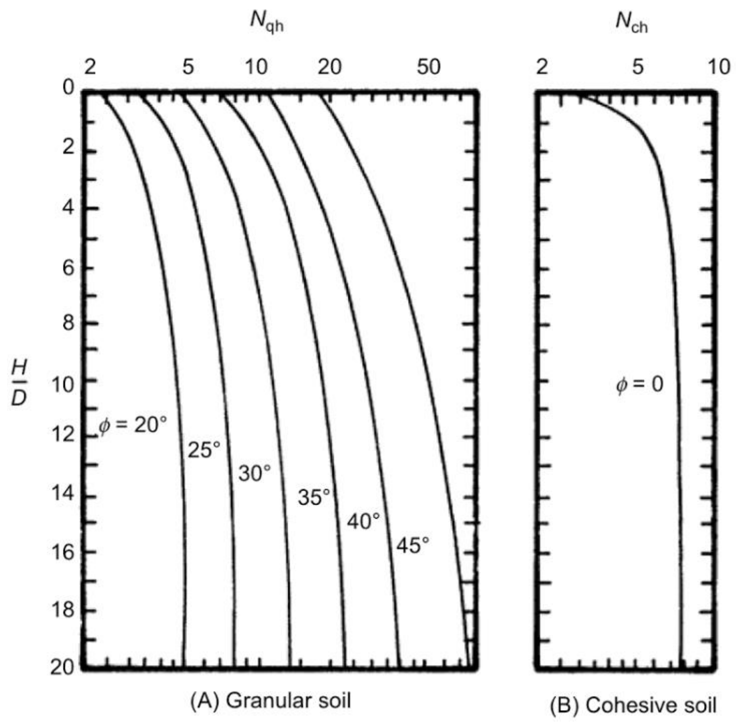


Figure 9-3 Horizontal bearing capacity factors [9]

The lateral soil resistance mobilization displacement;

$$\Delta_p = 0.04\left(H + \frac{D}{2}\right) \leq 0.10D \ to \ 0.15D.$$

9.4.6. Buried pipeline – vertical upward soil resistance

The uplift resistance R_{max} of a pipe in sand consists of two components, viz. a component owing to the weight of the soil above the pipe and a component owing to soil friction as per DNV-RP-F110 [6]. The uplift resistance can therefore be expressed as:

$$R_{max} = \left(1 + f\frac{H}{D}\right)(\gamma'_s HD)$$

The uplift resistance factor, f, is:

- $f = 0.1$ for loose sand (backfill)
- $f = 0.5$ for rockdump

The non-linear force-displacement response of a buried pipe is represented by a tri-linear curve as shown in the following figure.

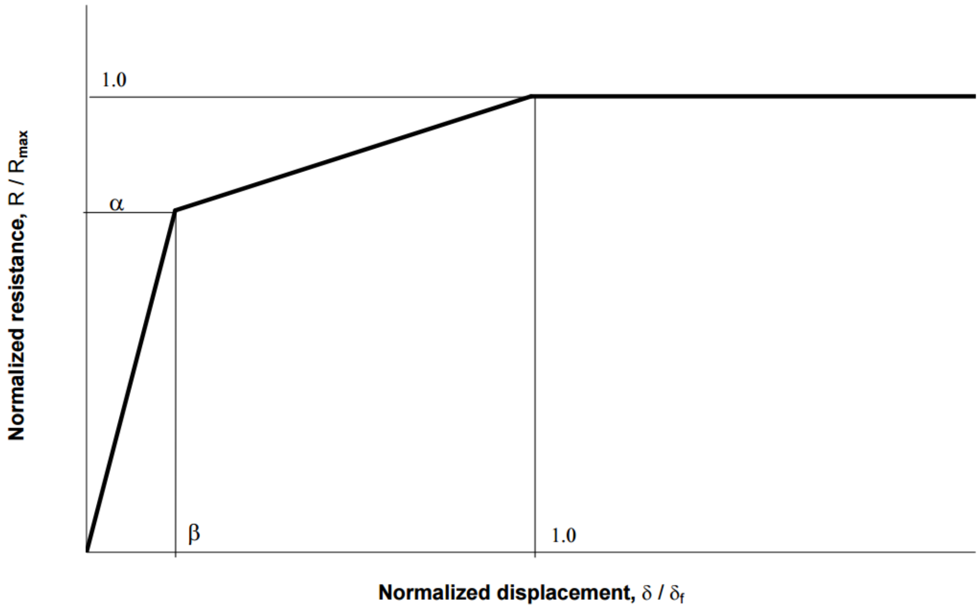


Figure 9-4 Uplift resistance Force-Deflection curve [6]

Where:

- δ_f = Failure displacement (=0.0065H for loose sand backfill) (=20mm for rock dump)
- $\alpha = 0.8$ for loose sand (backfill) and $\alpha = 0.7$ for rock dump
- $\beta = 0.2$

9.5. Results

9.5.1. Installation Load Case

For the Installation – Flooded load case, considering an as-surveyed seabed profile, the equivalent stress profile along the pipeline route is presented in Figure 9-5. Considering these results, pipeline stresses are found to be within the allowable limits as given by NEN3656 (Ref. [1]), with a maximum equivalent stress of 17 MPa at KP 7.943.

Pipeline free spans have been determined form the pipeline displacement results and are reported in Figure 9-6. As can be seen from these results all pipeline free spans are found to be below the allowable value and hence no seabed rectification work is required.

In addition, maximum pipeline free span gap heights are found to be well below the allowable of 0.5m, with a maximum of 0.046m.

Pipeline bottom roughness results for this load cases are summarised in the below Table.

Table 9-3: Results Summary – Installation Load Case

Property	Value
Maximum Equivalent Stress (MPa)	17
Allowable Equivalent Stress (MPa)	327
Location of Maximum Equivalent Stress (-)	KP 7.943
Maximum Free Span Length (m)	7.5
Location of Maximum Free Span (-)	KP 6.128
No. of Spans Exceeding the Allowable (-)	None
Allowable Span Length (m)	11
Maximum Span Gap Height (m)	0.046
Allowable Span Gap Height (m)	0.5
Location of Maximum Span Gap Height (-)	KP 8.731

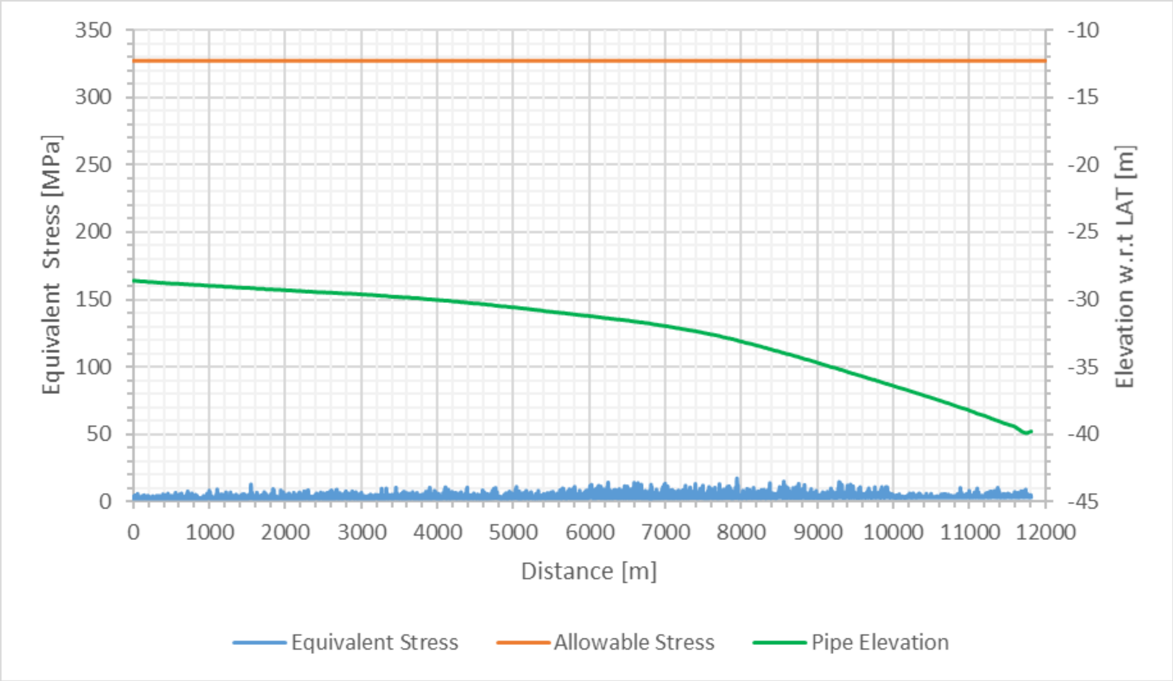


Figure 9-5: Equivalent Stress Profile – Installation, Flooded

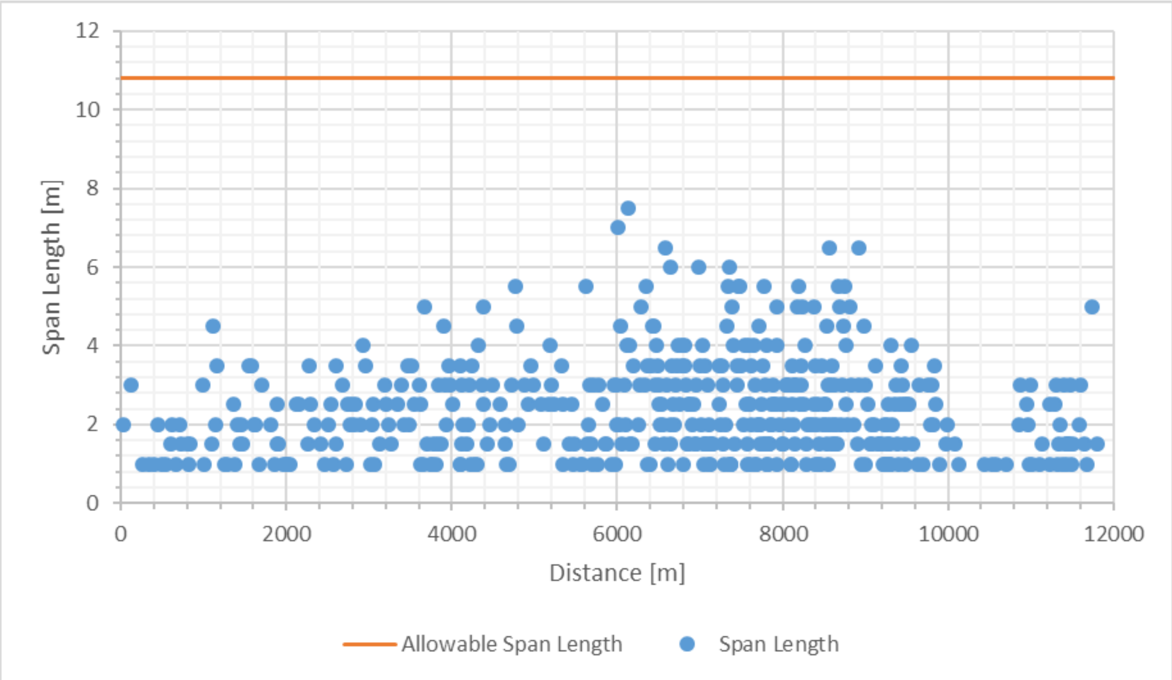


Figure 9-6: Pipeline Free Span Lengths – Installation, flooded

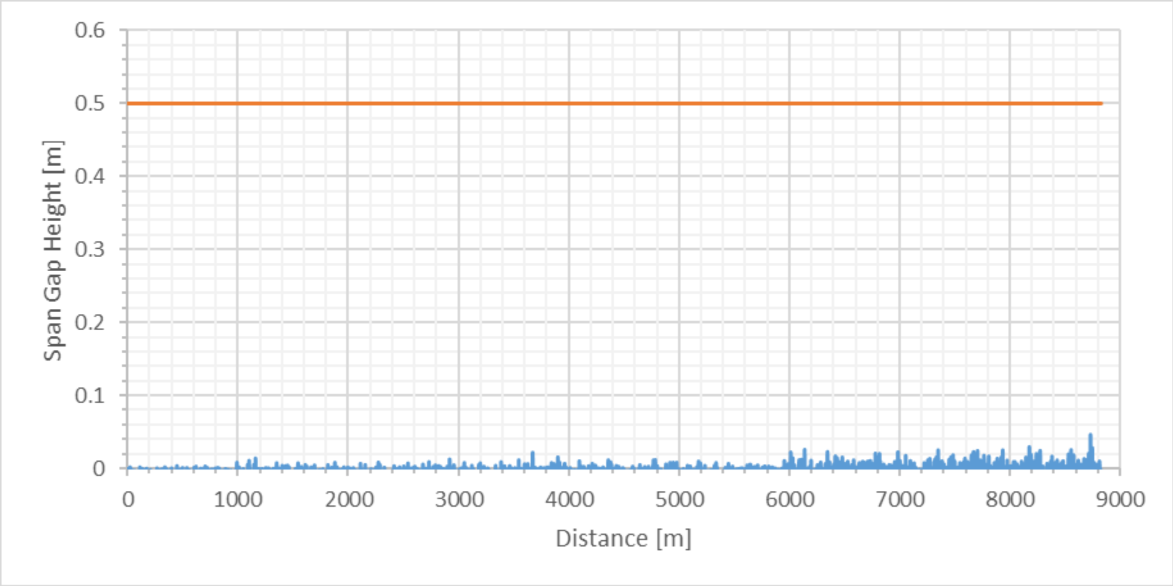


Figure 9-7: Pipeline Free Span Gap Heights – Installation, flooded

9.5.2. Hydrotest Load Case

For the Hydrotest load case, considering a buried ground profile and hydrotest pressure loading, the equivalent stress profile along the pipeline route is presented in Figure 9-8. Considering these results, pipeline stresses are found to be within the allowable limits as given by NEN 3656 with a maximum equivalent stress of 192 MPa at KP 7.942.

Figure 9-9 reports the axial force profile of the pipeline under the hydrotest loading, with a maximum force of 460 kN.

Figure 9-10 presents the axial displacement of the pipeline under the considered load. A maximum end displacement of 31 mm is determined with the anchor length being 280 m.

The pipeline free span length and gap height criteria are not applicable for this load case as the pipeline is considered buried.

Considering these results, the pipeline meets the design criteria as per NEN 3656 and hence no mitigation measures are required.

Pipeline bottom roughness results for this load case are summarised in the below Table.

Table 9-4: Results Summary - Hydrotest Load Case

Property	**Value**
Maximum Equivalent Stress (MPa)	192
Allowable Equivalent Stress (MPa)	327
Location of Maximum Equivalent Stress (-)	KP 7.942
Maximum Free Span Length (m)	Pipe Buried
Location of Maximum Free Span (-)	Pipe Buried
No. of Spans Exceeding the Allowable (-)	Pipe Buried
Allowable Span Length (m)	Pipe Buried
Maximum Span Gap Height (m)	Pipe Buried
Allowable Span Gap Height (m)	Pipe Buried
Location of Maximum Span Gap Height (-)	Pipe Buried

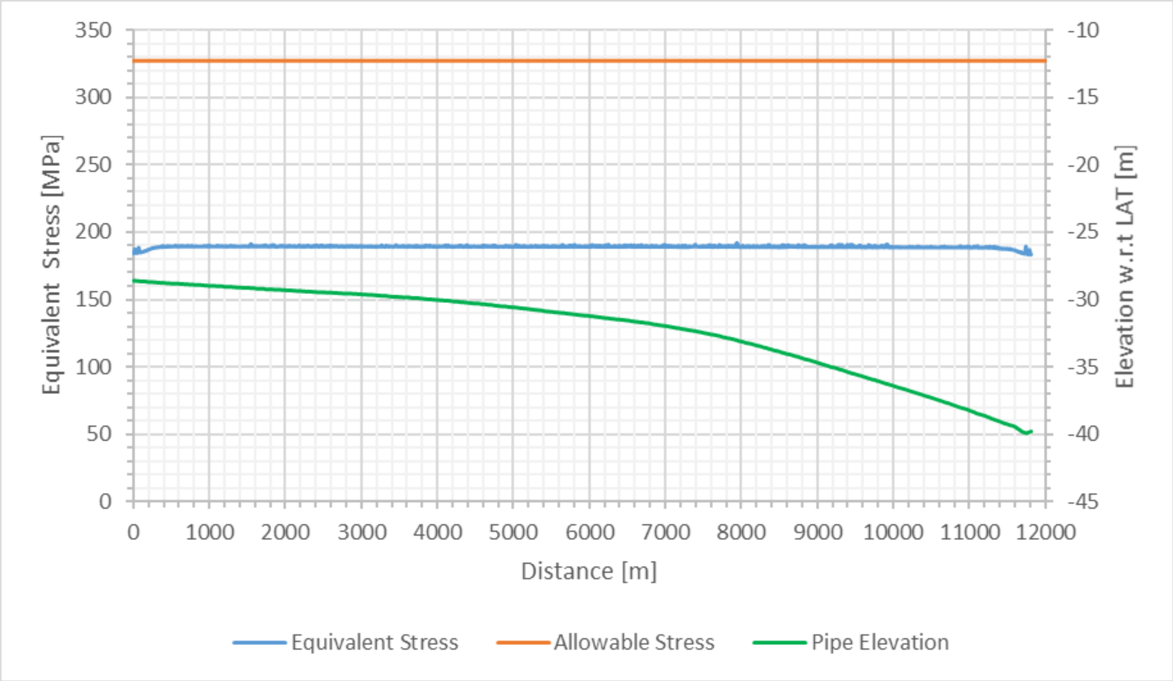


Figure 9-8: Equivalent Stress Profile – Hydrotest

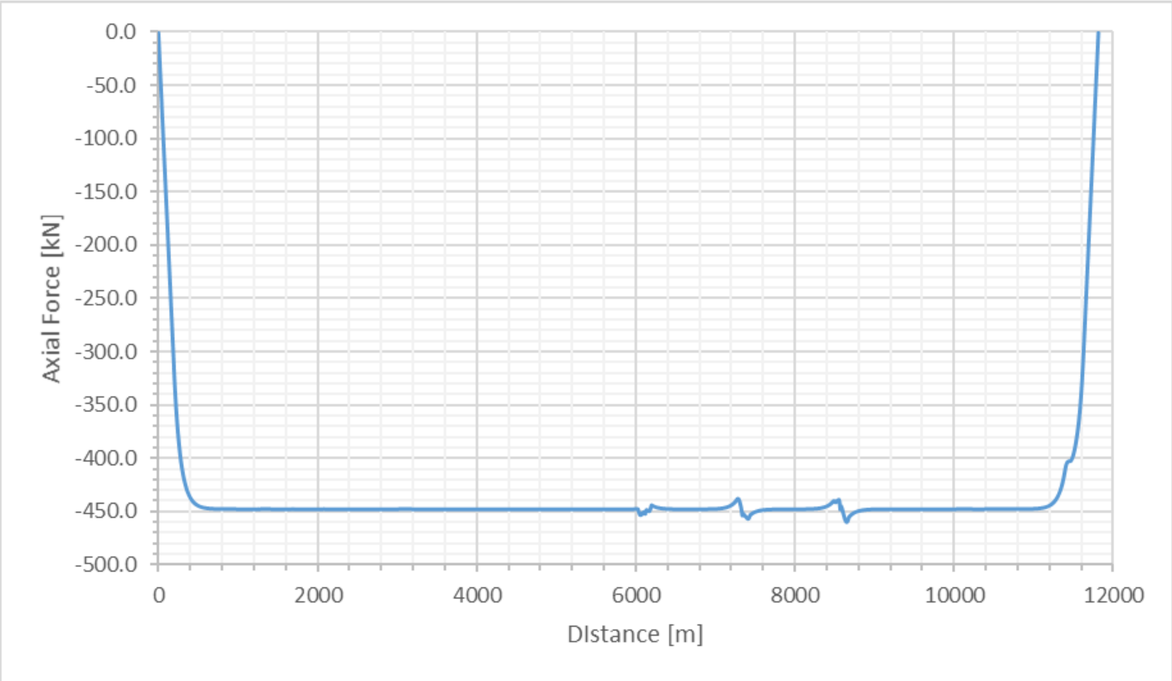


Figure 9-9: Pipeline Axial Force Profile – Hydrotest

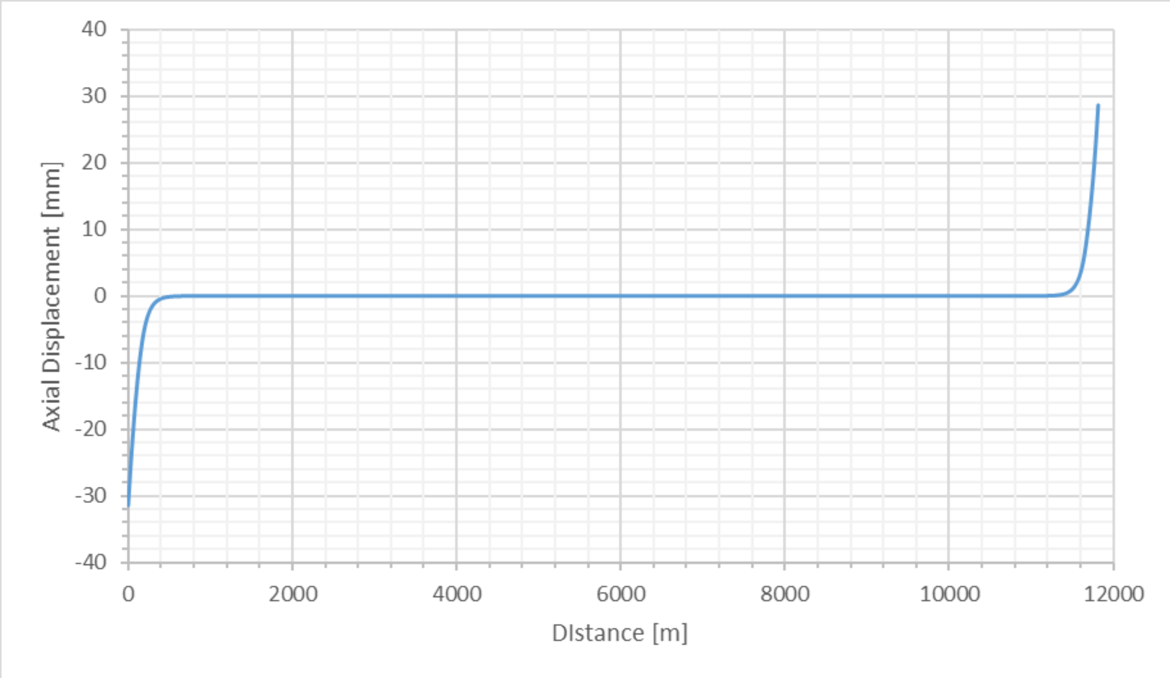


Figure 9-10: Pipeline Axial Displacement – Hydrotest

9.5.3. Operational Load Case – Nominal Wall Thickness

For the Operation load case, considering a buried ground profile and design temperature and pressure loading, with a nominal wall thickness the equivalent stress profile along the pipeline route is presented in Figure 9-11. Considering these results, pipeline stresses are found to be within the allowable limits as given by NEN 3656, with a maximum equivalent stress of 253 MPa at KP 9.287.

Figure 9-12 reports the axial force profile of the pipeline under the design conditions, with a maximum force of 2022 kN.

Figure 9-13 presents the axial displacement of the pipeline under the considered load. A maximum end displacement of 571 mm is determined with the anchor length being 1255 m.

Furthermore, no upheveal buckling of the pipeline has been observed, indicating that the burial depth is sufficient to supress buckling under the considered, conservative, uniform design temperature and pressure profile along the pipeline.

The pipeline free span length and gap height criteria are not applicable for this load case as the pipeline is considered buried.

Considering these results, the pipeline meets the design criteria as per NEN 3656 and hence no mitigation measures are required.

Pipeline bottom roughness results for this load case are summarised in the below Table.

Table 9-5: Results Summary – Operation Nominal WT Load Case

Property	Value
Maximum Equivalent Stress (MPa)	253
Allowable Equivalent Stress (MPa)	543
Location of Maximum Equivalent Stress (-)	KP 9.287
Maximum Free Span Length (m)	Pipe Buried
Location of Maximum Free Span (-)	Pipe Buried
No. of Spans Exceeding the Allowable (-)	Pipe Buried
Allowable Span Length (m)	Pipe Buried
Maximum Span Gap Height (m)	Pipe Buried
Allowable Span Gap Height (m)	Pipe Buried
Location of Maximum Span Gap Height (-)	Pipe Buried

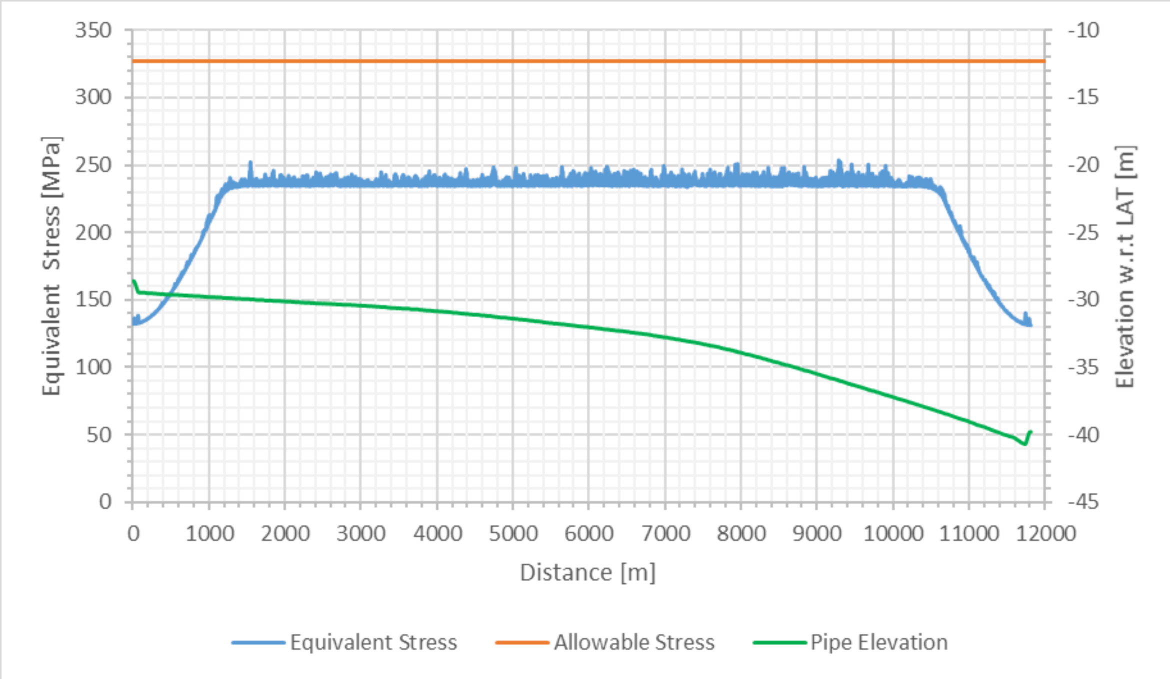


Figure 9-11: Equivalent Stress Profile – Operational - Nominal WT

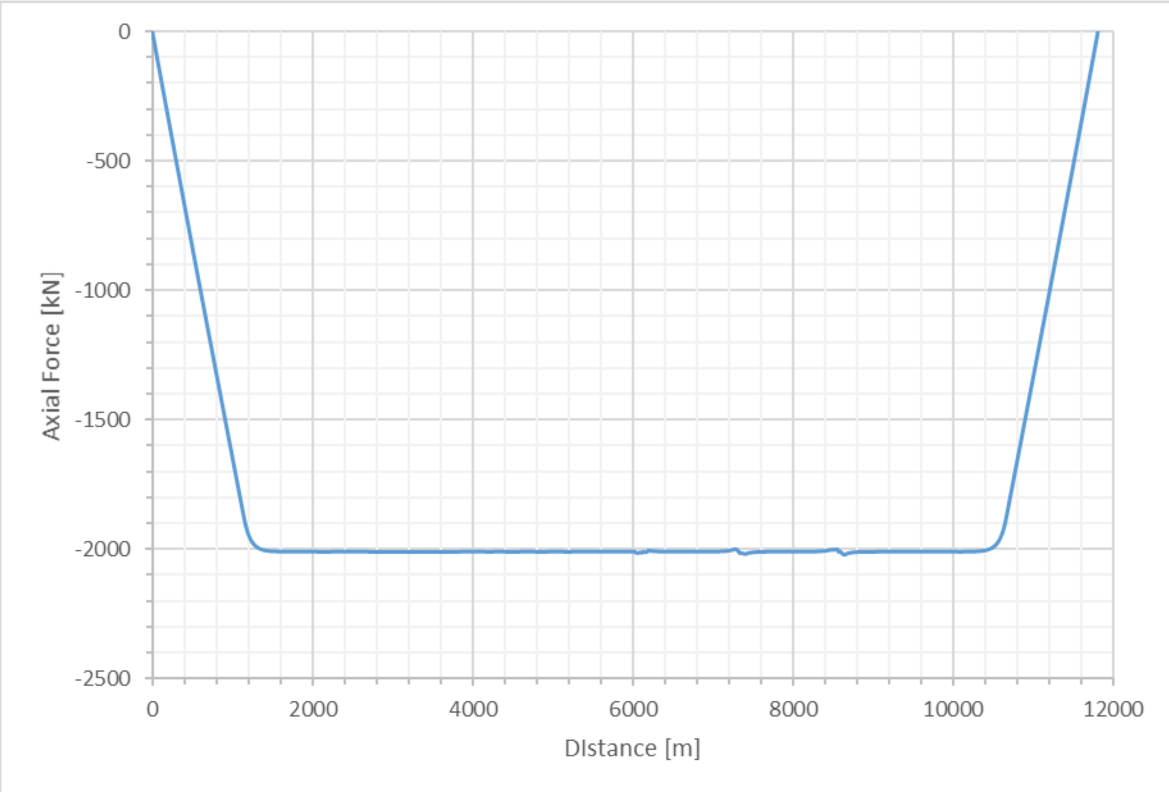


Figure 9-12: Pipeline Axial Force Profile – Operational - Nominal WT

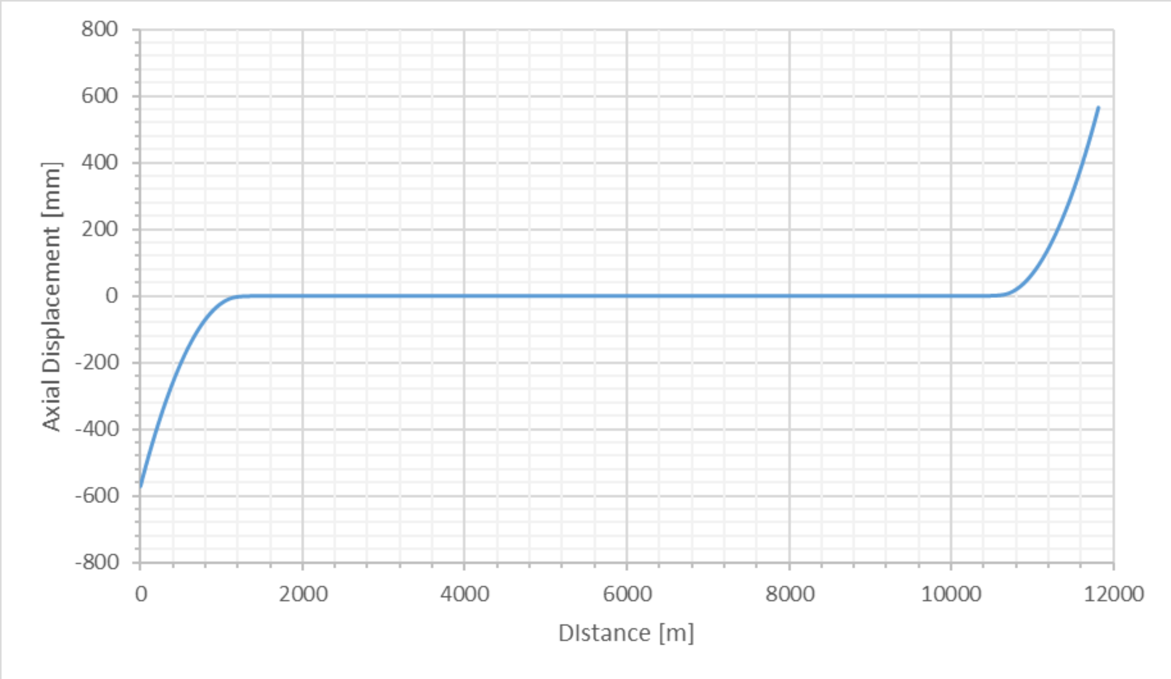


Figure 9-13: Pipeline Axial Displacement – Operational - Nominal WT

9.5.4. Operational Load Case – Corroded Wall Thickness

For the Operation load case, considering a buried ground profile and design temperature and pressure loading, with a fully corroded wall thickness the equivalent stress profile along the pipeline route is presented in Figure 9-8. Considering these results, pipeline stresses are found to be within the allowable limits as given by NEN 3656, with a maximum equivalent stress of 290 MPa at KP 6.028.

Figure 9-9 reports the axial force profile of the pipeline under the design conditions, with a maximum force of 1706 kN.

Figure 9-10 presents the axial displacement of the pipeline under the considered load. A maximum end displacement of 565 mm is determined with the anchor length being 1027 m.

The pipeline free span length and gap height criteria are not applicable for this load case as the pipeline is considered buried.

Furthermore, no upheveal buckling of the pipeline has been observed, indicating that the burial depth is sufficient to supress buckling under the considered, conservative, uniform design temperature and pressure profile along the pipeline.

Considering these results, the pipeline meets the design criteria as per NEN 3656 and hence no mitigation measures are required.

Pipeline bottom roughness results for this load case are summarised in the below Table.

Table 9-6: Results Summary – Operation Corroded WT Load Case

Property	Value
Maximum Equivalent Stress (MPa)	290
Allowable Equivalent Stress (MPa)	543
Location of Maximum Equivalent Stress (-)	KP 6.028
Maximum Free Span Length (m)	Pipe Buried
Location of Maximum Free Span (-)	Pipe Buried
No. of Spans Exceeding the Allowable (-)	Pipe Buried
Allowable Span Length (m)	Pipe Buried
Maximum Span Gap Height (m)	Pipe Buried
Allowable Span Gap Height (m)	Pipe Buried
Location of Maximum Span Gap Height (-)	Pipe Buried

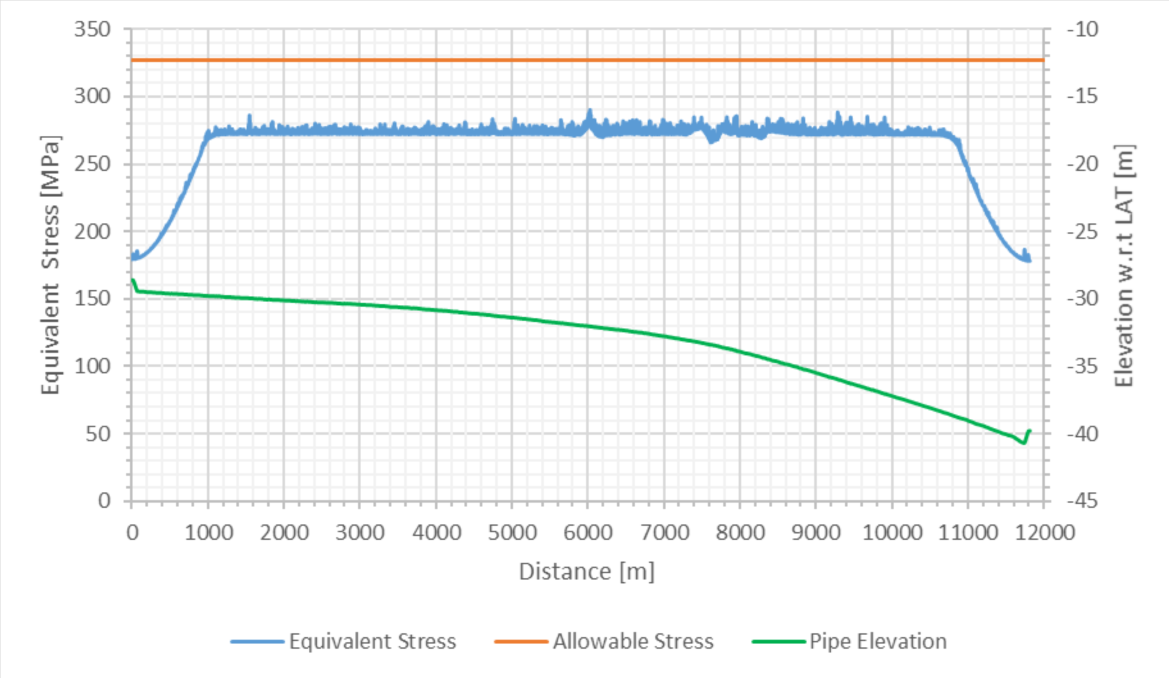


Figure 9-14: Equivalent Stress Profile – Operational - Corroded WT

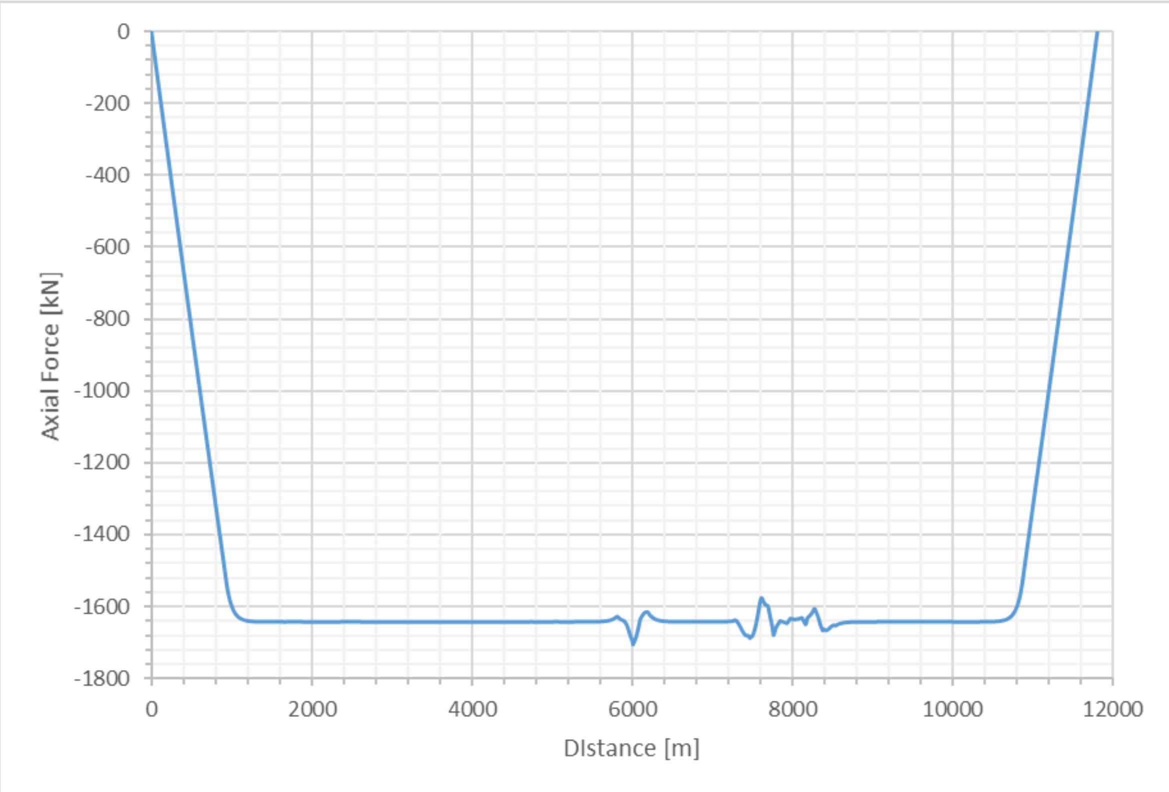


Figure 9-15 Pipeline Axial Force Profile – Operational - Corroded WT

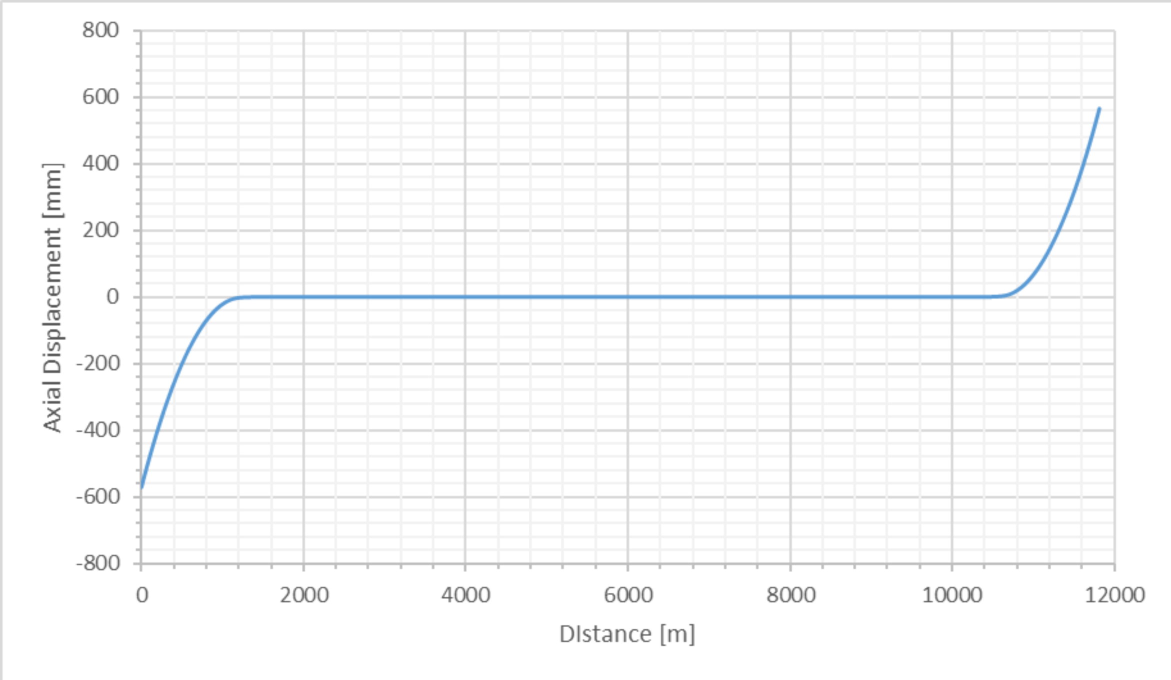


Figure 9-16: Pipeline Axial Displacement – Operational - Corroded WT

10. Upheaval Buckling

10.1. General

When a buried pipeline is operated at a temperature and pressure higher than ambient it will try to expand. If the line is not free to expand, the pipe will develop an axial compressive force. If the force exerted by the pipe on the soil exceeds the vertical restraint against uplift movement created by the pipe's submerged weight, its bending stiffness and the resistance of the soil cover, the pipe will tend to move upward which ultimately may result in buckling. This phenomenon, referred to as upheaval buckling (UHB), has been checked for the pipeline since it is operated at an elevated temperature. The following sections will present the UHB analysis and results for both the Analytical – and the FEM analyses.

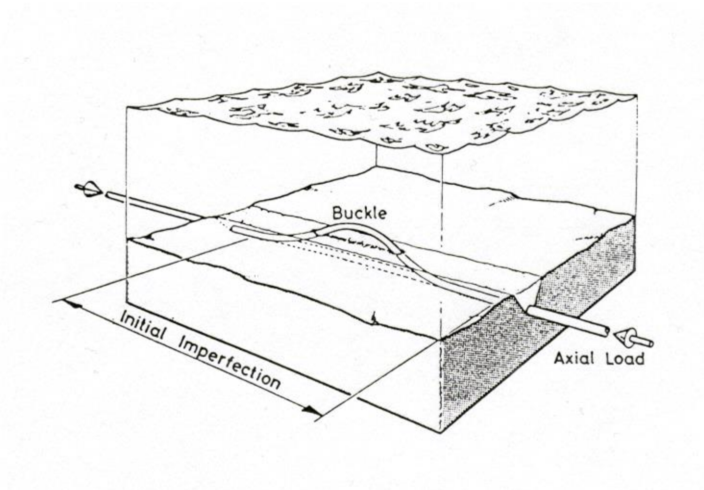


Figure 10-1 Pipeline Upheaval Buckling

10.2. Method

Buried pipelines exposed to compressive effective axial forces may get unstable beyond its anchor point and move vertically out of the seabed if the cover has insufficient resistance. An out-of-straightness configuration will result in forces acting on the cover, perpendicular to the pipeline. In case these vertical forces exceed the cover resistance the pipeline will buckle upwards.

The analytical upheaval buckling assessment is performed for the pipeline based on [11]. This method determines the relation between the minimum required cover height, the imperfection height and the length of the imperfection. The analysis is performed for the maximum design temperature and pressure (65 degree C, 148 barg) as well as an operating temperature of 40 degree C and 148 barg.

Parameters in the assessment of upheaval buckling are the dimensionless imperfection length (Φ_L) and the dimensionless maximum download parameter (Φ_w). These are given by:

$$\Phi_L = L\sqrt{\frac{N_e}{EI}}$$

And:

$$\Phi_w = \frac{w\,E\,I}{\delta\,N_e^2}$$

Where

L is the imperfection/exposure length

N_e is effective axial compressive force

$E\ I$ is the bending stiffness

is the required download

δ is the imperfection height

Depending on the value of Φ_L, the required download is derived from Φ_w in accordance with:

$$\Phi_w = 0.0646 \text{ for } \Phi < 4.49$$

$$\Phi_w = \frac{5.68}{\Phi_L^2} - \frac{88.35}{\Phi_w^4} \text{ for } 4.49 < \Phi < 8.06$$

$$\Phi_w = \frac{9.6}{\Phi_L^2} - \frac{343}{\Phi_w^4} \text{ for } \Phi > 8.06$$

The upload resistance by the soil cover is given in cohesionless soils by:

$$q = \gamma\,H\,OD\left(1 + f\frac{H}{OD}\right)$$

Where:

q is the upload resistance

γ is the submerged weight of the soil

H is the depth of the cover

OD is the outside diameter of the pipe

f is the uplift coefficient (0.5 for dense material, 0.1 for loose material)

The calculated required download must be smaller than the actual combination of the submerged weight and uplift resistance of the pipeline.

The applied method is conservative, in that it does not model a number of mitigating factors. As the pipe moves upwards in the early stage of buckling, the effective actual force is reduced. The buried pipe is also limited in the movement in axial direction, which limits how far the pipeline can slide towards the developing buckle.

Furthermore, the assumed sinusoidal imperfection profile assumed in the model is envisaged to yield conservative download requirements. The results will be presented as a maximum imperfection length with respect to the cover depth and the imperfection length.

10.3. Results

The calculation of the minimum length to accommodate an imperfection has been performed for an operating pressure of 148 barg and temperatures of resp. 65 C and 40 C. As the sand is fairly loose over the pipe, it requires time to settle after backfilling of the trench, a submerged density of 850 kg/m3 and an uplift coefficient of 0.2 were used.

The minimum length was found at the intersection between the available and required download, as seen in Figure 10-2. This minimum length was obtained for the range of imperfection heights and cover depths, and is gathered in Table 10-1 and table 10.2 for a pressure of 148 barg and a temperature of resp. 65 C and 40 C. Appendix D shows the calculations performed for a single cover depth and imperfection height.

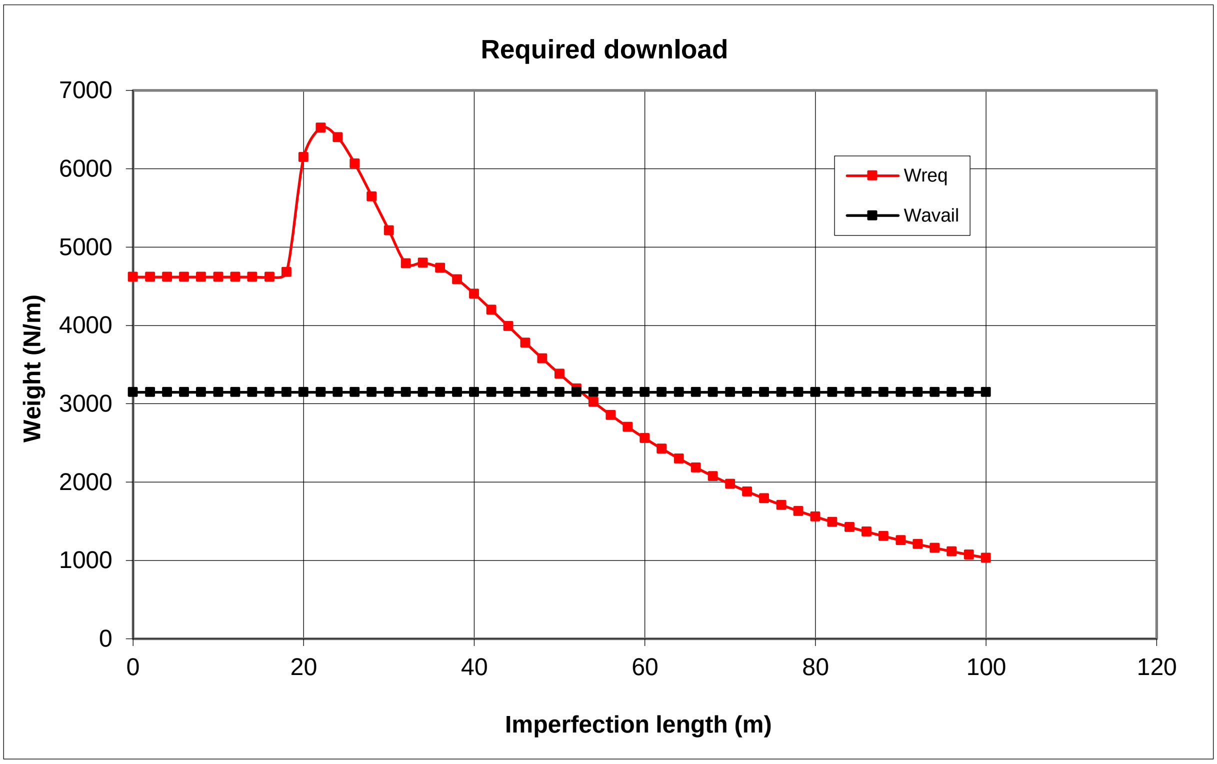


Figure 10-2 Required and available download for an imperfection height of 1 m and a cover depth of 0.8 m, as a function of imperfection length (pressure = 148 barg; temperature = 40 C.)

Table 10-1 Required length to accommodate an imperfection of given height for a given cover depth (pressure = 148 barg; temperature = 65 C.)

Min. required Imperfection Length (m)		Cover Height to TOP [m]													
		1.4	1.3	1.2	1.1	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Available Download, q [N/m]		6742	6059	5410	4794	4212	3662	3146	2664	2215	1799	1416	1067	751	469
Imperfection Height [m]	0.05	x	x	x	x	x	x	x	x	x	x	x	x	x	36
	0.1	x	x	x	x	x	x	x	x	x	x	x	32	44	58
	0.15	x	x	x	x	x	x	x	x	x	x	36	44	56	72
	0.2	x	x	x	x	x	x	x	x	32	38	46	54	66	84
	0.25	x	x	x	x	x	x	x	32	38	44	52	60	74	94
	0.3	x	x	x	x	x	x	34	38	44	50	58	68	80	>100
	0.35	x	x	x	x	x	34	38	42	48	54	62	72	88	>100
	0.4	x	x	x	x	34	38	42	46	52	58	68	78	94	>100
	0.45	x	x	x	32	38	42	46	50	56	62	72	84	100	>100
	0.5	x	x	32	36	40	44	48	54	60	66	76	88	>100	>100
	0.55	x	32	36	40	42	46	52	56	62	70	80	92	>100	>100
	0.6	x	34	38	42	46	50	54	60	66	74	84	96	>100	>100
	0.65	34	38	40	44	48	52	56	62	68	76	86	100	>100	>100
	0.7	36	40	42	46	50	54	58	64	72	80	90	>100	>100	>100
	0.75	38	42	44	48	52	56	62	68	74	82	94	>100	>100	>100
	0.8	40	44	46	50	54	58	64	70	76	86	96	>100	>100	>100
	0.85	42	44	48	52	56	60	66	72	80	88	100	>100	>100	>100
	0.9	44	46	50	54	58	62	68	74	82	90	>100	>100	>100	>100
	0.95	44	48	52	56	60	64	70	76	84	94	>100	>100	>100	>100
	1	46	50	54	56	62	66	72	78	86	96	>100	>100	>100	>100

Table 10-2 Required length to accommodate an imperfection of given height for a given cover depth (pressure = 148 barg; temperature = 40 C.)

Min. required Imperfection Length (m)		Cover Height to TOP [m]													
		1.4	1.3	1.2	1.1	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Available Download, q [N/m]		6742	6059	5410	4794	4212	3662	3146	2664	2215	1799	1416	1067	751	469
Imperfection Height [m]	0.05	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	0.1	x	x	x	x	x	x	x	x	x	x	x	x	x	38
	0.15	x	x	x	x	x	x	x	x	x	x	x	x	32	54
	0.2	x	x	x	x	x	x	x	x	x	x	x	30	48	64
	0.25	x	x	x	x	x	x	x	x	x	x	28	42	56	74
	0.3	x	x	x	x	x	x	x	x	x	28	38	50	62	80
	0.35	x	x	x	x	x	x	x	x	26	32	44	54	68	88
	0.4	x	x	x	x	x	x	x	x	30	40	50	60	74	94
	0.45	x	x	x	x	x	x	x	28	32	44	54	64	78	100
	0.5	x	x	x	x	x	x	26	30	40	48	58	68	82	>100
	0.55	x	x	x	x	x	x	28	32	44	52	60	72	86	>100
	0.6	x	x	x	x	x	26	30	40	48	56	64	76	92	>100
	0.65	x	x	x	x	24	30	32	44	50	58	68	78	96	>100
	0.7	x	x	x	x	28	30	40	46	54	60	70	82	98	>100
	0.75	x	x	x	26	30	32	44	50	56	64	72	86	>100	>100
	0.8	x	x	x	28	30	40	46	52	58	66	76	88	>100	>100
	0.85	x	x	26	30	32	42	48	54	60	68	78	92	>100	>100
	0.9	x	x	28	30	38	44	50	56	62	70	80	94	>100	>100
	0.95	x	26	28	32	40	46	52	58	64	72	82	96	>100	>100
	1	x	28	30	36	42	48	54	60	66	74	86	100	>100	>100

11. Cathodic Protection

In compliance with NEN 3656 the cathodic protection system of the pipeline will be designed as per ref.[12].

The characteristics of a typical anode element are given in Table 11-1. The datasheet for the specific bracelet anode chosen can be found in Appendix E.2.

Table 11-1: Typical anode characteristics

Item	Value
Type	Half Shell Bracelet
Material	Aluminium
ID_anode	273 [mm]
wt_anode	38 [mm]
Length_anode	321 [mm]
Anode mass (half bracelet)(1)	16.5 [kg]
Note 1: calculated mass is higher than the catalogue value, as the gap and taper is disregarded.	

The cathodic protection will be designed to prevent external corrosion of the pipeline, throughout the operational lifetime, as specified in Table- 11-1. The mass and spacing of the anodes will be such that the following criteria are met:

Total anode mass to meet the mean and final current demand over the design life of the pipeline.

- Anode current output to meet the required current output at the end of the design life.
- Anode separation not to exceed a value of 300 m.
- Anode spacing shall consider the temperature gradient of the pipeline, as given in Figure 4-1;

11.1. Design current density

The pipeline will be divided in to sections where changes in conditions, such as water depth, operating temperature or burial can give rise to variations in design current density.

From the pipeline dimensions and the coating selected, the mean current demand, I_{cm}, and the final demand, I_{cf}, shall be calculated separately as per the following:

$$I_c = A_c \cdot f_c \cdot i_c$$

Where:
I_c = the current demand for a specific pipeline section calculated for mean and final conditions [A]
A_c = the total surface area for a specific pipeline section [m^2]
f_c = the coating breakdown factor determined for mean and final conditions [-]
i_c = the current density selected for mean and final conditions [A/m^2]

For pipelines fully buried, a design current density (mean and final) of 20 [mA/m^2] should be used irrespective of seawater temperature, oxygen content or depth as per Section 7.4.3 of Ref. . In addition, pipelines operating with temperatures in excess of 25 [°C] on the outside metallic surface of the pipe require an adjustment to the design current density. The design current densities shall be increased by 1 [mA/m^2] for each degree Celsius of the metal/environment above 25 [°C] up to 100 [°C] as per Section 7.4.3 of Ref. [12]. The appropriate relations are summarized in Table 11-2.

Table 11-2 Current density according ISO 15892-2 section 7.4

			design current density	Buried	Submerged
if T ≤	25	ºC :	i =	0,020	1/LN(T/1.5)*125+4*LN(T)+10
if T ≥	25	ºC :	i =	i<25 +0.001*(T-25)	

11.2. Coating break-down

The coating breakdown factors for mean and final conditions, f_c, taking into consideration the deign life of the pipeline, are calculated as follows.

The mean coating breakdown factor, $\overline{f_c}$, is determined by:

$$\overline{f_c} = f_i + (0.5\Delta f \cdot t_{dl})$$

And the final coating breakdown factor, f_f , is determined by

$$f_f = f_i + (\Delta f \cdot t_{dl})$$

Where:
f_i = the initial coating breakdown factor at the start of pipeline operation [-]
Δf = the average yearly increase in the coating breakdown factor [-]
t_{dl} = the design life [yrs]

The initial coating breakdown factor and average yearly increase in breakdown factor are dependent on the anti-corrosion coating and field joint coating material. Values for various coating are taken from Ref. [12] and reported in Table 11-3. For project specific coating system and for the field joint application, the following options is considered:

- a three-layer polyethylene line pipe coating in combination with heat shrink sleeves (HSS);

Table 11-3: Coating breakdown factors [12]

Factory-applied coating type	Field joint coating type	f_i	Δf
Fusion-bonded epoxy (FBE)	Heat-shrinkable sleeves (HSS[a])	0,080	0,003 5
	FBE	0,060	0,003 0
Three-layer coating systems including epoxy, adhesive and polyethylene (3LPE)	HSS[a]	0,009	0,000 6
	FBE	0,008	0,005
	Multilayer coating including epoxy and PE (e.g. moulded, HSS[a] or flame spray)	0,007	0,000 5
Three-layer coating systems including epoxy, adhesive and polypropylene (3LPP)	HSS[a]	0,007	0,000 3
	FBE	0,006	0,000 2
	Multilayer coating including epoxy and PP (e.g. HSS[a], hot tapes, moulding or flame spray)	0,005	0,000 2
Heat insulation multilayer coating systems including epoxy, adhesive and/or PE, PP or PU	Thick multilayer coating systems including epoxy, adhesive and/or PE, PP, PU, HSS[a] or a combination of these products.	0,002	0,000 1
Thick coatings: elastomeric materials (e.g. polychloroprene or EPDM) or glassfibre-reinforced resins	Thick elastomeric materials or glassfibre-reinforced resins	0,002	0,000 1
Flexible pipelines	Not applicable (mechanical couplings)	0,002	0,000 1

[a] HSS can be used with or without primer.

Having established the mean current demand, the total required mass of anode material for a specific pipeline section is determined as follows:

$$m = I_{cm} \cdot t_{dl} \cdot \frac{8760}{\mu \cdot \varepsilon}$$

Where:
m = the total net anode mass, for the specific pipeline section [kg]
I_{cm} = the mean current demand for the specific pipeline section [A]
µ = is the utilization factor (-) = 0.8 for bracelet anodes as per Section 8.4 of Ref.[12].
ε = the electrochemical capacity of the anode material per kilogram [A/h]

11.3. Electrochemical properties

The electrochemical capacity of the anode material is dependent on the surface temperature of the anode and its burial status. The applicable values are taken from Section 8.3 of Ref. [12] and reported in Table 11-4, where linear interpolation is used to calculate the electrochemical properties along the pipeline.

Having determined the total net anode mass required to meet the current demand, the minimum number of anodes required in a specific pipeline section, will be determined as follows:

$$n = \frac{m}{m_a}$$

Where:
n = the number of anodes to be installed on the specific pipeline section [-]
m_a = the individual net anode mass [kg]

The minimum number of anodes, n, shall be determined considering the maximum allowable anode spacing of 300m as reported in Section 8.1 of Ref. [12].

Table 11-4: Electrochemical properties for galvanic anodes [12]

Anode type	Anode surface temperature[a]	Immersed in seawater		Buried in seawater sediments[d]	
		Potential	Electrochemical capacity	Potential	Electrochemical capacity
		Ag/AgCl/ seawater	ε	Ag/AgCl/ seawater	ε
	°C	mV	A·h/kg	mV	A·h/kg
Aluminium	< 30	− 1 050	2 000	− 1 000	1 500
	60	− 1 050	1 500	− 1 000	800
	80[b]	− 1 000	900	− 1 000	400
Zinc	< 30	− 1 030	780	− 980	750
	> 30 to 50[c]			− 980	580
Electrochemical capacity for a given alloy is a function of temperature and anode current density. Reference is made to Annex A for guidance on CP design for variations in anode current densities. For non-buried pipelines, the anode surface temperature should be taken as the external pipeline temperature and not the internal fluid temperature. For buried pipelines, the anode surface temperature shall be taken as the internal fluid temperature.					
[a] For anode surface temperatures between the limits stated, the electrochemical capacity shall be interpolated. [b] For aluminium anodes, the anode surface temperature shall not exceed 80 °C unless the performance has been demonstrated in tests and has been documented. [c] For zinc anodes, the anode surface temperature shall not exceed 50 °C unless satisfactory performance has been demonstrated in tests and has been documented. [d] Pipelines which are rock-dumped shall be considered as buried in seawater sediments.					

To provide the required current, the actual anode current output shall be greater than or equal to the required current output:

$$I_{af} \geq I_f$$

Where:
I_{af} = the actual end-of-life individual current output [A]
I_f = the required end-of-life individual anode current output [A]

The required end-of-life individual anode current output, I_f, shall be calculated from the following:

$$I_f = \frac{I_{cf}}{n}$$

Where:
I_{cf} = the total current demand for the protection of the specific pipeline section at the end of life [A]

For a given anode size and mass, the actual individual anode current output at the end of life, I_{af}, is calculated from the below equation:

$$I_{af} = \frac{E_c - E_a}{R_a}$$

Where:
E_c = the design protection potential [V]
E_a = the design closed-circuit potential of the anode [V]
R_a = the total circuit resistance, which is assumed to be equivalent to the anode resistance [Ω]

The anode resistance, R_a, shall be calculated as follows:

$$R_a = 0.315\frac{\rho}{\sqrt{A}}$$

Where:
ρ = the environmental resistivity [Ω.m]
A = the exposed surface area of the anode [m^2]

To determine the end-of-design-life anode-to-seawater resistance, the anodes shall be assumed to be consumed to an extent given by their utilization factor. The approximate anode dimensions (exposed surface area) corresponding to this degree of degradation shall be used in the anode resistance formula for R_a.

11.4. Results

Table 11-5 presents the required number of anodes and the spacing between anodes for locations along the pipeline. Table 11-6 presents the summary of the complete pipeline

Detail output of the calculations can be found in Appendix E.1. An additional 2 anodes per spool piece should be considered, these are not part of the number of anodes calculated. For the cathodic protection system calculation, the pipeline has been discretized into sections of 219.6 [m], or 18 x 12.2 [m] meter joints (typical joint length). Conservatively, the inlet temperature per discrete section is used per section input.

Table 11-6: Cathodic Protection Anode spacing

Location	Anodes required (per nr. of joints)	Anode spacing [m]
KP 0.0 – KP 0.22	5 (1/3.6 joints)	43.9
KP 0.22 – KP 0.44	3 (1/6 joints)	73.2
KP 0.44 – KP 1.10	2 (1/9 joints)	109.8
KP 1.10 – End	1 (1/18 joints)	219.6

Table 11-6: Cathodic Protection System Summary

Total Required Net Anode Mass [kg]	Total Net Anode Mass Installed [kg]	Maximum final Current Demand [A]	Final Anode Current Output [A]	Total Number of Anodes(1,2)
912.2	1055.1	0.102	0.231	64
Note 1: total number of anodes is for pipeline only and does not include anodes on spool pieces Note 2: single half bracelet anode Net mass = 16.5 [kg] Note 3: valid for Temperature < 25 ^{0}C, local anode spacing may change due to temperature effects				

APPENDIX A Wall Thickness Calculations

A.1 Wall Thickness Calculation – Pressure Containment – Inside 500 m Zone

A.2 Wall Thickness Calculation – Pressure Containment – Outside 500 m Zone

A.3 Wall Thickness Calculation – Buckling and Collapse – Installation

A.4 Wall Thickness Calculation – Buckling and Collapse – Hydrotest

A.5 Wall Thickness Calculation – Buckling and Collapse – Operation

A.1 Wall Thickness Calculation – Pressure Containment – Inside 500 m Zone

(2 pages)

Project	**: D12-B Pipeline Detailed Design**
Project #	: 18004.500
Subject	: Wall thickness calculation pipeline
File #	: 18004-60-CAL-01501-01-01
Client	: Wintershall Noordzee BV
Client File #	: D12B-67031002-PL-LA0580-GLOBAL-001
Originator	: VH
Date	: 12.7.2018
Revision	: 01
Checked	: PF

10" Pipeline - Inside 500m zone

Material properties

Material		=	L360NB	
Design temperature	T_d	=	65	°C
Yield at ambient temperature	R_e	=	360.00	N/mm^2
Yield at design temperature	R_{ed}	=	343.20	N/mm^2
Material factor (Table 4 NEN 3656)	γ_m	=	1.10	-
Allowable stress $\sigma_v = \frac{R_{ed}}{\gamma_m}$	σ_v	=	312.00	N/mm^2

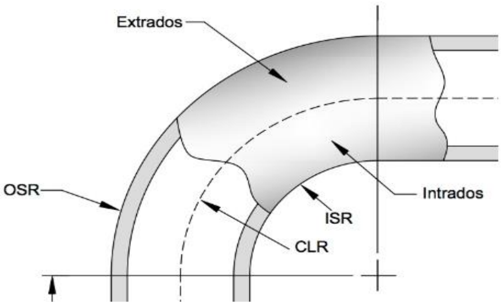
Pipeline properties

Outside diameter	OD	=	273.1	mm
Design pressure	P_d	=	148	barg
Minimum outside presssure	P_o	=	0	barg
Fabrication Tolerance	f_{tol}	=	5.5	%
Corrosion allowance	CA	=	3	mm
Pipeline within the 500 meter zone?			y	(Y or N)
Load factor (Table 3 NEN 3656): 1,25 outside 500m zone; 1,364 inside 500m zone	γ_s	=	1.364	-
Bend radius			1366	mm
Fabrication tolerance bends	f_{tolB}	=	5.5	%
Inside bend factor $\frac{2R-0.5D_e}{2R-D_e}$		=	1.06	
Outside bend factor $\frac{2R+0.5D_e}{2R+D_e}$		=	0.95	

Minimum wall thickness determination, d_{min}

$$d_{min} = \frac{\gamma_m \cdot \gamma_s \cdot P_d^* \cdot D_e}{2 \cdot R_e(T_d) + \gamma_m \cdot \gamma_s \cdot P_d^*}$$

minimum wall thickness (excl. CA):	=	8.56	mm
Inside bend	=	9.03	mm
Outside bend	=	8.17	mm



Minimum required wall thickness (incl. CA) after bending, d_{min} [Note 2]

Straight part / along bend radius @ CLR	=	11.56	mm
Inside bend @ ISR	=	12.03	mm
Outside bend @ OSR	=	11.17	mm
Selected nominal wall thickness	=	12.7	mm

Project	**:**	**D12-B Pipeline Detailed Design**
Project #	**:**	18004.500
Subject	**:**	Wall thickness calculation pipeline
File #	**:**	18004-60-CAL-01501-01-01
Client	**:**	Wintershall Noordzee BV
Client File #	**:**	D12B-67031002-PL-LA0580-GLOBAL-001

Originator : VH   Checked : PF
Date : 12.7.2018
Revision : 01

10" Pipeline - Inside 500m zone

Hoop stress

Hoop stress straight parts $\sigma_{hoop} = \frac{\gamma_s \cdot P_d^* \cdot (D_e - d_{min})}{2 \cdot d_{min}}$ = 296.14 N/mm^2

Hoop stress inside bend $\sigma_{hoop}(BI) = \frac{2 \cdot R - \frac{1}{2} \cdot D_e}{2 \cdot R - D_e} \cdot \sigma_{hoop}$ = 312.59 N/mm^2

Hoop stress outside bend $\sigma_{hoop}(BO) = \frac{2 \cdot R + \frac{1}{2} \cdot D_e}{2 \cdot R + D_e} \cdot \sigma_{hoop}$ = 282.68 N/mm^2

Stress Check

Hoop stress (N/mm2)	Occurring	Allowable	
Straight parts	296.14	312.00	
Inside bend	312.59	312.00	[Note 3]
Outside bend	282.68	312.00	

Test pressure

Hydrotest temperature = 15 °C
Yield at hydrotest temperature = 360 N/mm^2

Product (gas / others) gas
Design factor, CP (1.3 for gas; 1.25 for others) 1.30

Minimum hydrotest pressure $P_{T,min} = C_p \cdot P_d \cdot \frac{R_e(20^\circ C)}{R_e(T_d)}$ = 201.82 barg

Maximum allowable hydrotest pressure $P_{T,max} = \frac{2 \cdot d_{nom} \cdot (1 - f_{tol}) \cdot R_e(20^\circ C)}{(D_e - d_{nom} \cdot (1 - f_{tol}))}$ = 330.95 barg

Mill test pressure $P_{T,mill} = 0.9 \cdot \frac{2 \cdot R_e \cdot d_{nom}}{D_e}$ = 301.34 barg

Max. allowable hydro test pressure exceeds mill test pressure!!

Note 1: Outside 500m zone: Pd***** = (Pd - Pe)
Within 500m zone: Pd***** = Pd
Note 2: The bend manufacturer to ensure that the finished products does meet with these minimum WT. requirements.
Note 3: Inside bend is slightly overstressed taken into account the straight pipe fabrication tolerance of 5.5% and a corrosion allowance of 3 mm.
However it's assumed that the inside bend will be at least 5-10% thicker due to the bending process.

A.2 Wall Thickness Calculation – Pressure Containment – Outside 500 m Zone

(2 pages)

Project	**: D12-B Pipeline Detailed Design**
Project #	: 18004.500
Subject	: Wall thickness calculation pipeline
File #	: 18004-60-CAL-01501-02-01
Client	: Wintershall Noordzee BV
Client File #	: D12B-67031002-PL-LA0580-GLOBAL-002_Wall thickness_10x12.7_out 500m.xlsx

Originator	: VH	Checked	: PF
Date	: 12.7.2018		
Revision	: 01		

10" Pipeline - Outside 500m zone

Material properties

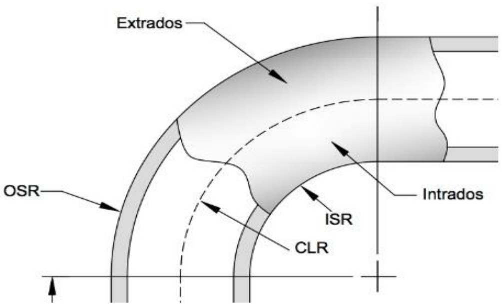
Material			=	L360NB	
Design temperature		T_d	=	65	°C
Yield at ambient temperature		R_e	=	360.00	N/mm^2
Yield at design temperature		R_{ed}	=	343.20	N/mm^2
Material factor (Table 4 NEN 3656)		γ_m	=	1.10	-
Allowable stress	$\sigma_v = \frac{R_{ed}}{\gamma_m}$	σ_v	=	312.00	N/mm^2

Pipeline properties

Outside diameter		OD	=	273.1	mm
Design pressure		P_d	=	148	barg
Minimum outside presssure		P_o	=	2.5	barg
Fabrication Tolerance		f_{tol}	=	5.5	%
Corrosion allowance		CA	=	3	mm
Pipeline within the 500 meter zone?				n	(Y or N)
Load factor (Table 3 NEN 3656):		γ_s	=	1.250	-
1,25 outside 500m zone; 1,364 inside 500m zone					
Bend radius				1366	mm
Fabrication tolerance bends		f_{tolB}	=	5.5	%
Inside bend factor	$\frac{2R - 0.5D_e}{2R - D_e}$		=	1.06	
Outside bend factor	$\frac{2R + 0.5D_e}{2R + D_e}$		=	0.95	

Minimum wall thickness determination, d_{min}

minimum wall thickness (excl. CA):	$d_{min} = \frac{\gamma_m \cdot \gamma_s \cdot P_d^* \cdot D_e}{2 \cdot R_e(T_d) + \gamma_m \cdot \gamma_s \cdot P_d^*}$	=	7.73	mm
Inside bend		=	8.16	mm
Outside bend		=	7.38	mm



Minimum required wall thickness (incl. CA) after bending, d_{min} [Note 2]

Straight part / along bend radius @ CLR	=	10.73	mm
Inside bend @ ISR	=	11.16	mm
Outside bend @ OSR	=	10.38	mm

Selected nominal wall thickness	=	12.7	mm

Project	**: D12-B Pipeline Detailed Design**
Project #	: 18004.500
Subject	: Wall thickness calculation pipeline
File #	: 18004-60-CAL-01501-02-01
Client	: Wintershall Noordzee BV
Client File #	: D12B-67031002-PL-LA0580-GLOBAL-002_Wall thickness_10x12.7_out 500m.xlsx
Originator	: VH
Date	: 12.7.2018
Revision	: 01
Checked	: PF

10" Pipeline - Outside 500m zone

Hoop stress

Hoop stress straight parts $\sigma_{hoop} = \frac{\gamma_s \cdot P_d^* \cdot (D_e - d_{\min})}{2 \cdot d_{\min}}$ = 266.81 N/mm^2

Hoop stress inside bend $\sigma_{hoop}(BI) = \frac{2 \cdot R - \frac{1}{2} \cdot D_e}{2 \cdot R - D_e} \cdot \sigma_{hoop}$ = 281.63 N/mm^2

Hoop stress outside bend $\sigma_{hoop}(BO) = \frac{2 \cdot R + \frac{1}{2} \cdot D_e}{2 \cdot R + D_e} \cdot \sigma_{hoop}$ = 254.68 N/mm^2

Stress Check

Hoop stress (N/mm2)	Occurring	Allowable
Straight parts	266.81	312.00
Inside bend	281.63	312.00
Outside bend	254.68	312.00

Test pressure

Hydrotest temperature = 15 °C

Yield at hydrotest temperature = 360 N/mm^2

Product (gas / others) gas

Design factor, CP (1.3 for gas; 1.25 for others) 1.30

Minimum hydrotest pressure $P_{T,\min} = C_p \cdot P_d \cdot \frac{R_e(20^\circ C)}{R_e(T_d)}$ = 201.82 barg

Maximum allowable hydrotest pressure $P_{T,\max} = \frac{2 \cdot d_{nom} \cdot (1 - f_{tol}) \cdot R_e(20^\circ C)}{(D_e - d_{nom} \cdot (1 - f_{tol}))}$ = 330.95 barg

Mill test pressure $P_{T,mill} = 0.9 \cdot \frac{2 \cdot R_e \cdot d_{nom}}{D_e}$ = 301.34 barg

Max. allowable hydro test pressure exceeds mill test pressure!!

Note 1: Outside 500m zone: Pd***** = (Pd - Pe)
Within 500m zone: Pd***** = Pd

Note 2: The bend manufacturer to ensure that the finished products does meet with these minimum WT. requirements.

A.3 Wall Thickness Calculation – Buckling and Collapse – Installation

(14 pages)

Project	: **D12-B Detailed Pipeline Design**		
Project #	: 18004.500		
Subject	: Buckling and Collapse		
File #	: 18004-60-CAL-01504-01-01 - B&C_10in x 12.7mm_installation flooded		
Client	: Wintershall Noordzee		
Client File #	: D12B-67031002-PL-LA0580-GLOBAL-005		
Originator	: PF	Checked	: EvW
Date	: 09.07.2018		
Revision	: 01		

Buckling and Collapse - 10in x 12.7mm - Installation: filled

Situation

1. Installation: empty
2. Installation: filled
3. Hydrotest
4. Operational

2
Installation: filled

	Pressure (barg)	Temperature (deg. C)
Installation (P_{in}, T_{in})	2	15
Design (P_d, T_d)	148	65
Hydrotest (P_t, T_t)	202	15

Pipeline properties

Nominal diameter		OD_{nom} =	10"	
Nominal diameter		OD_{nom} =	273.1	mm
Nominal wall thickness		d_{nom} =	12.7	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	4.45	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	4.45	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	277.545	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	268.655	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.016	-
Cross sectional area of steel		A =	10389	mm^2
Moment of Inertia		I =	88271060	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	5.5	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	9.0	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	264.1	mm

Piggyback

Nominal diameter	$OD_{nom,p}$ =	0	mm
Nominal wall thickness	$d_{nom,p}$ =	0.0	mm

Coating data

Thickness line pipe	=	2.8	mm
Thickness piggyback	=	0	mm
Density	=	900	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Project	**:**	**D12-B Detailed Pipeline Design**
Project #	**:**	18004.500
Subject	**:**	Buckling and Collapse
File #	**:**	18004-60-CAL-01504-01-01 - B&C_10in x 12.7mm_installation flooded
Client	**:**	Wintershall Noordzee
Client File #	**:**	D12B-67031002-PL-LA0580-GLOBAL-005

Originator	: PF	Checked	: EvW
Date	: 09.07.2018		
Revision	: 01		

Material = L360NB

Design temperature	T_d =	15	°C
Yield at ambient temperature	R_e =	360.00	N/mm^2
Yield at design temperature	R_{ed} =	360.00	N/mm^2
Density	ρ_{st} =	7850	kg/m^3
Youngs modulus	E_s =	210000	N/mm^2
Poisson's ratio	u =	0.3	-
Linear thermal expansion coefficient	a =	1.16E-05	m/m/°C

Contents

Sea water density		1025	kg/m^3
Pipeline product density		0.1	kg/m^3
Pipeline content density used for this case:	Installation: filled	1025	kg/m^3

Pipeline Weights

$$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$$

Pipeline weight in air	$W_{pl,a}$ =	1306.1	N/m
Piggyback weight in air	$W_{pg,a}$ =	0.0	N/m

$$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$$

Buoyancy force pipeline	$F_{B,pl}$ =	613.4	N/m
Buoyancy force piggyback	$F_{B,pb}$ =	0.0	N/m
Submerged pipeline weight,empty	$W_{pl,s,e}$ =	208.1	N/m
Submerged piggyback weight	$W_{pg,s}$ =	0.0	N/m
Total submerged bundle weight,empty	$W_{T,s,e}$ =	208.1	N/m
Total submerged bundle weight,water filled	$W_{T,s,f}$ =	692.6	N/m

Soil

Submerged density		ρ_{ss} =	1000	kg/m^3
Depth of burial		d_b =	0.80	m
Soil cover pressure	$SC_{pres} = r_{ss} \times d_b \times g$	SC_{pres} =	0.008	N/mm^2

Environmental conditions

Water depths:

Seawater density		ρ_{sw} =	1025	kg/m3
Maximum water depth		WD_{max} =	40	m LAT
Minimum water depth		WD_{min} =	28.6	m LAT
Other water depth (to be used for calculations)		WD =	28.6	m LAT
Storm surge, RP1 yr		ss_{1yr} =	-0.85	m LAT
Storm surge, RP100 yr		ss_{100yr} =	-1.24	m LAT
Storm surge water level	SSWL = WD + ss	SSWL =	27.75	m LAT
Highest Astronomical Tide		HAT =	2.29	m

Waves (H_{max} & T_{max}): from SW direction (bearing 140 deg)

Maximum wave height, RP1 yr - installation/hydrotes	$H_{max,1}$ =	11.3	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$ =	9.7	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$ =	16.2	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$ =	11.7	s

Project : **D12-B Detailed Pipeline Design**
Project # : 18004.500
Subject : Buckling and Collapse
File # : 18004-60-CAL-01504-01-01 - B&C_10in x 12.7mm_installation flooded

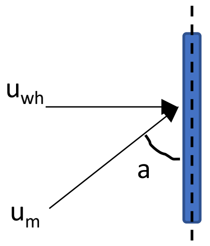
Client : Wintershall Noordzee
Client File # : D12B-67031002-PL-LA0580-GLOBAL-005

Originator	: PF	Checked	: EvW
Date	: 09.07.2018		
Revision	: 01		

Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$\frac{H_{max}}{g\cdot T_z^2} =$ 0.0122

$\frac{SWL}{g\cdot T_z^2} =$ 0.0301



Wave theory selected:			
1. Airy/linear wave; 2. Stokes 5th	**2**	Stokes 5th	
Maximum wave particle velocity	u_{wm} =	2.03	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	2.03	m/s

Current:

Height above seabed at which velocity is known	z* =	0.286	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.31	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.33	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	0.36	m/s
Current velocity at reference height	U_{czr} =	0.31	m/s
Angle of attack relative to pipeline axis	α_{uc} =	90	deg
Horizontal current velocity ⊥ to P/L $\frac{7}{8}\cdot U_{czr}\cdot\left(\frac{OD_{nom}}{z_r}\right)^{1/7}\cdot\sin(\alpha_{uc}) =$	u_{ch} =	0.27	m/s

Hydrodynamic coefficients:

Drag coefficient	C_D =	0.7	-
Lift coefficient	C_L =	0.9	-
Inertia coefficient	C_I =	3.29	-

Maximum absolute hydrodynamic force 572 N/m

Temperatures:

Ambient temperature T_{amb} = 4 deg. C

Collapse - external pressure only (K.3.3.5.1)

External implosion pipe collapse pressure (P_c) given by:

$$(p_c - p_e)\cdot(p_c^2 - p_p^2) = p_c\cdot p_e\cdot p_p\cdot 2\cdot\delta_o\cdot\frac{OD_g}{d_{nom}}$$

External elastical pipe collapse pressure (P_e): $P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3$ = 51.3 N/mm^2

External plastic pipe collapse pressure (P_p) $P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$ = 33.5 N/mm^2

External implosion pipe collapse pressure (P_c): P_c = 19.8 N/mm^2

Maximum water column above mudline (WC_{max}) $WC_{max} = WD_{max} + 0.5\cdot H_{max,100} + HAT$ = 50.39 m
0.5039 N/mm^2

Actual external pressure (P_L) $WC_{max} + SC_{pres}$ = 0.51 N/mm^2

Assessment: $\gamma_{g,p} \cdot P_L \leq \dfrac{\gamma_M \cdot P_c}{\gamma_{m,p}}$ **Where,**

Table 4 - NEN3656

$g_{g,p}$ =	1.05	-
g_M =	0.93	-
$g_{m,p}$ =	1.45	-

Assessment: $\gamma_{g,p} \cdot P_L \leq \dfrac{\gamma_M \cdot P_c}{\gamma_{m,p}}$ **= OK**

Collapse - bending moment only (K.3.3.5.2)

Buckling bending moment (M_c) $M_c = D_g^2 d_n R_e$ = 3.2E+08 N·mm

Assessment: $\gamma_{g,M} \times M_L \leq \dfrac{\gamma_M \times M_c}{\gamma_{m,M}}$ **Where,**

Table 4 - NEN3656

$g_{g,M}$ =	1.1	-
g_M =	1	-
$g_{m,M}$ =	1.3	-

Maximum allowable bending moment ($M_{L,b}$) $M_{L,b}$ = 2.2E+08 N·mm

= 2.230E+05 N·m

Collapse - external pressure + bending moment only (K.3.3.5.3)

Assessment: $\dfrac{\gamma_{g,p} \times P_L}{P_c / \gamma_{m,p}} + \left(\dfrac{\gamma_{g,M} \times M_L}{M_c / \gamma_{m,M}} \right)^n \leq \gamma_M$ **Where,**

Table 4 - NEN3656

$g_{g,p}$ =	1.05	-
$g_{g,M}$ =	1.55	-
$g_{m,p}$ =	1.25	-
$g_{m,M}$ =	1.15	-
g_M =	0.93	-
$n = 1 + 300 \cdot d_{nom} / OD_g$ n =	15.4	-

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.6E+08 N·mm

= 1.571E+05 N·m

Determination maximum span length due to bending only or bending & external pressure

Assessment: $M_{L,m} = \dfrac{q \cdot L^2}{10}$ **Where,**

q = load acting on pipe

L = span length

$$q = \sqrt{\gamma_W{}^2 \cdot W_S{}^2 + \gamma_H{}^2 \cdot (F_D + F_I)^2}$$

Ws = submerged pipeline weight; Ws =	693	N/m
$F_D + F_I$ =	572	N/m
g_w =	1.1	-
g_h =	1.2	-
Table 3 - NEN3656		
q =	1025	N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.6E+05 N·m

Maximum span length, L_{max} = 39.1 m

Progressive plastic collapse (K.3.3.6)

Assessment: $$\varepsilon_{max} = \alpha \times \Delta T \le \left[\frac{R_e(\theta)}{E} \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_p}{R_e(\theta)}\right)^2} + \frac{R_e}{E}\sqrt{0{,}9 - \frac{3}{4}\left(\frac{\sigma_p}{R_e}\right)^2} \right]$$

Temperature difference with ambient; DT	=	11	-
R_e	=	360.00	N/mm²
R_{ed}	=	360.00	N/mm²
s_p	=	2.9	N/mm²

$$\sigma_p = \frac{p \cdot (OD_{nom} - d_{min})}{2 \cdot d_{min}}$$

$$\varepsilon_{max} = \alpha \times \Delta T \le \left[\frac{R_e(\theta)}{E} \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_p}{R_e(\theta)}\right)^2} + \frac{R_e}{E}\sqrt{0{,}9 - \frac{3}{4}\left(\frac{\sigma_p}{R_e}\right)^2} \right]$$

Assessment: 0.0001 < 0.0033 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 20.8 **OK**

Bar buckling:

Assessment: $$L_{max,bb} = \sqrt{4 \cdot \pi^2 \frac{E \cdot I}{|N|}}$$

Effective axial force $N = A \cdot (\nu \cdot S_h - \gamma_t \cdot E \cdot \alpha \cdot \Delta T)$

$S_h = g_p \cdot s_h$ — Table 3 - NEN3656 - BC4

g_p	=	1.15	-
g_t	=	1.1	-
N	=	-2.96E+05	N
$L_{max,bb}$	**=**	**49.7**	**m**

Stokes 5th order wave theory

Water depth	WD =	28.6	m (LAT)
Storm surge	ss =	-0.85	m
Storm surge water level	$SWL = WD + ss$ =	27.75	m
Wave height	H =	11.3	m
Wave period	T =	9.7	s
Grav. Acceleration	g =	9.81	m/s^2
Deep water wave length	$L_o = \frac{g \cdot T^2}{2 \cdot \pi}$ =	146.9	m

Solving for wave length (L) and λ

$$\frac{\pi \cdot H}{SWL} - \frac{L}{SWL}\left\{\lambda + \lambda^3 \cdot B_{33} + \lambda^5 \cdot (B_{35} + B_{55})\right\} = 0 \quad (\text{I})$$

$$\frac{SWL}{L_O} - \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) \cdot \left\{1 + \lambda^2 \cdot C_1 + \lambda^4 \cdot C_2\right\} = 0 \quad (\text{II})$$

Choosing L and solving for λ in (II) results in 4 roots for λ

Estimate actual wave length, L **138.168 m**

$A = SWL / L_O$ = 0.1889

$B = \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right)$ = 0.1710

$$\lambda = \pm \sqrt{X}$$

$$X = \frac{-C_1 \cdot B \pm \sqrt{D}}{2 \cdot C_2 \cdot B}$$

$D = (C_1 \cdot B)^2 - 4 \cdot (C_2 \cdot B) \cdot (-(A - B))$ = 0.1301

	-	eq. (I)	eq. (II)
λ1	0.239	-0.0001	0.0000
λ2	Numerator of X < 0		
λ3	-0.239	2.5586	0.0000
λ4	Numerator of X < 0		

Item	Formula	Value	Unit
s	$s = \sinh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.6246	-
c	$c = \cosh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.9077	-
A11	$A_{11} = \frac{1}{s} =$	0.6155	-
A13	$A_{13} = \frac{-c^2 \cdot (5 \cdot c^2 + 1)}{8 \cdot s^5} =$	-0.7717	-
	$A_{15} = -\frac{1184 \cdot c^{10} - 1440 \cdot c^8 - 1992 \cdot c^6 + 2641 \cdot c^4 - 249 \cdot c^2 + 18}{1536 \cdot s^{11}} =$	-1.3810	-
A22	$A_{22} = \frac{3}{8 \cdot s^4} =$	0.0538	-
A24	$A_{24} = \frac{192 \cdot c^8 - 424 \cdot c^6 - 312 \cdot c^4 + 480 \cdot c^2 - 17}{768 \cdot s^{10}} =$	0.1102	-
A33	$A_{33} = \frac{13 - 4 \cdot c^2}{64 \cdot s^7} =$	-0.0008	-
	$A_{35} = \frac{512 \cdot c^{12} + 4224 \cdot c^{10} - 6800 \cdot c^8 - 12808 \cdot c^6 + 16704 \cdot c^4 - 3154 \cdot c^2 - 107}{4096 \cdot s^{13} \cdot (6 \cdot c^2 - 1)} =$	0.0488	-
A44	$A_{44} = \frac{80 \cdot c^6 - 816 \cdot c^4 + 1338 \cdot c^2 - 197}{1536 \cdot s^{10} \cdot (6 \cdot c^2 - 1)} =$	-0.0006	-

$$A_{55} = -\frac{2880 \cdot c^{10} - 72480 \cdot c^8 + 324000 \cdot c^6 - 432000 \cdot c^4 + 163470 \cdot c^2 - 16245}{61440 \cdot s^{11} \cdot (6 \cdot c^2 - 1) \cdot (8 \cdot c^4 - 11 \cdot c^2 + 3)} =$$ 0.0000 -

B22 $$B_{22} = \frac{(2 \cdot c^2 + 1) \cdot c}{4 \cdot s^3} =$$ 0.9208 -

B24 $$B_{24} = \frac{c \cdot (272 \cdot c^8 - 504 \cdot c^6 - 192 \cdot c^4 + 322 \cdot c^2 + 21)}{384 \cdot s^9} =$$ 1.3909 -

B33 $$B_{33} = \frac{3 \cdot (8 \cdot c^6 + 1)}{64 \cdot s^6} =$$ 0.9857 -

$$B_{35} = \frac{88128 \cdot c^{14} - 208224 \cdot c^{12} + 70848 \cdot c^{10} + 54000 \cdot c^8 - 21816 \cdot c^6 + 6264 \cdot c^4 - 54 \cdot c^2 - 81}{12288 \cdot s^{12} \cdot (6 \cdot c^2 - 1)} =$$
= 3.6412 -

B44 $$B_{44} = c \cdot \frac{768 \cdot c^{10} - 488 \cdot c^8 - 48 \cdot c^6 + 48 \cdot c^4 + 106 \cdot c^2 - 21}{384 \cdot s^9 \cdot (6 \cdot c^2 - 1)} =$$ 1.2201 -

$$B_{55} = \frac{192000 \cdot c^{16} - 26720 \cdot c^{14} + 83680 \cdot c^{12} + 20160 \cdot c^{10} - 7280 \cdot c^8 + 7160 \cdot c^6 - 1800 \cdot c^4 - 1050 \cdot c^2 + 225}{12288 \cdot s^{10} \cdot (8 \cdot c^4 - 11 \cdot c^2 + 3) \cdot (6 \cdot c^2 - 1)} =$$
= 1.7227 -

C1 $$C_1 = \frac{8 \cdot c^4 - 8 \cdot c^2 + 9}{8 \cdot s^4} =$$ 1.5404 -

$$C_2 = \frac{3840 \cdot c^{12} - 4096 \cdot c^{10} + 2592 \cdot c^8 - 1008 \cdot c^6 + 5944 \cdot c^4 - 1830 \cdot c^2 + 147}{512 \cdot s^{10} \cdot (6 \cdot c^2 - 1)} =$$ 4.9664 -

C3 $$C_3 = -\frac{1}{4 \cdot c \cdot s} =$$ -0.0807 -

C4 $$C_4 = \frac{12 \cdot c^8 + 36 \cdot c^6 - 162 \cdot c^4 + 141 \cdot c^2 - 27}{192 \cdot c \cdot s^9} =$$ 0.0755 -

K1 $$K_1 = \lambda \cdot A_{11} + \lambda^3 \cdot A_{13} + \lambda^5 \cdot A_{15} =$$ 0.1356 -

K2	$K_2 = \lambda^2 \cdot A_{22} + \lambda^4 \cdot A_{24} =$	0.0034	-
K3	$K_3 = \lambda^3 \cdot A_{33} + \lambda^5 \cdot A_{35} =$	0.0000	-
K4	$K_4 = \lambda^4 \cdot A_{44} =$	0.0000	-
K5	$K_5 = \lambda^5 \cdot A_{55} =$	0.0000	-

Horizontal wave particle velocities

Water depth at which data required, z (w.r.t. seabed) 0.2731 m

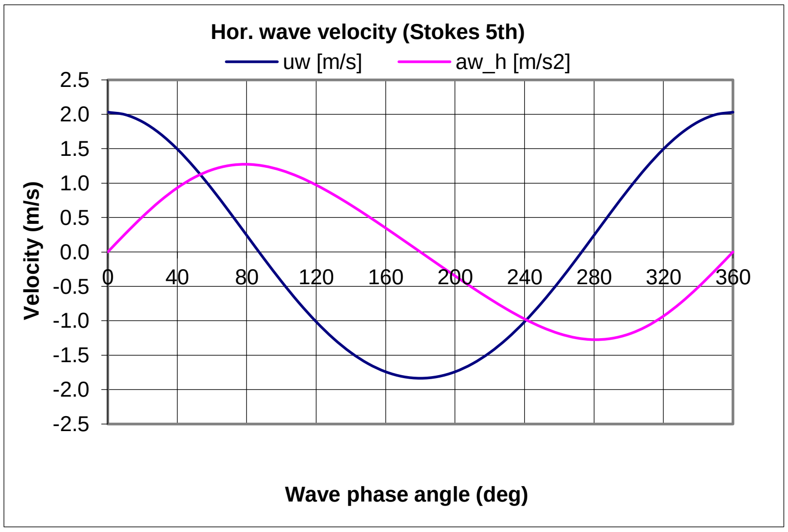
Horizontal velocity, u_w

$$u_w = \frac{L}{T} \cdot \sum_{n=1}^{5} n \cdot K_n \cdot \cosh\left(n \cdot \frac{2 \cdot \pi}{L} \cdot z\right) \cdot \cos(n \cdot \varphi)$$

Horizontal acceleration, $a_{w,h}$

$$a_{w,h} = \frac{2 \cdot \pi \cdot L}{T^2} \cdot \sum_{n=1}^{5} n^2 \cdot K_n \cdot \cosh\left(n \cdot \frac{2 \cdot \pi}{L} \cdot z\right) \cdot \sin(n \cdot \varphi)$$

ϕ [deg.]	uw [m/s]	aw_h [m/s^2]
0.00	2.0310	0.0000
10.00	1.9956	0.2617
20.00	1.8911	0.5114
30.00	1.7222	0.7378
40.00	1.4965	0.9314
50.00	1.2238	1.0850
60.00	0.9158	1.1940
70.00	0.5846	1.2567
80.00	0.2426	1.2741
90.00	-0.0982	1.2491
100.00	-0.4272	1.1868
110.00	-0.7349	1.0928
120.00	-1.0138	0.9734
130.00	-1.2577	0.8345
140.00	-1.4622	0.6812
150.00	-1.6239	0.5181
160.00	-1.7408	0.3485
170.00	-1.8114	0.1751
180.00	-1.8350	0.0000
190.00	-1.8114	-0.1751
200.00	-1.7408	-0.3485



210.00	-1.6239	-0.5181
220.00	-1.4622	-0.6812
230.00	-1.2577	-0.8345
240.00	-1.0138	-0.9734
250.00	-0.7349	-1.0928
260.00	-0.4272	-1.1868
270.00	-0.0982	-1.2491
280.00	0.2426	-1.2741
290.00	0.5846	-1.2567
300.00	0.9158	-1.1940
310.00	1.2238	-1.0850
320.00	1.4965	-0.9314
330.00	1.7222	-0.7378
340.00	1.8911	-0.5114
350.00	1.9956	-0.2617
360.00	2.0310	0.0000

U_{wm} = max. wave particle velocity = 2.03 m/s

Originator	: PF	Checked	: EvW
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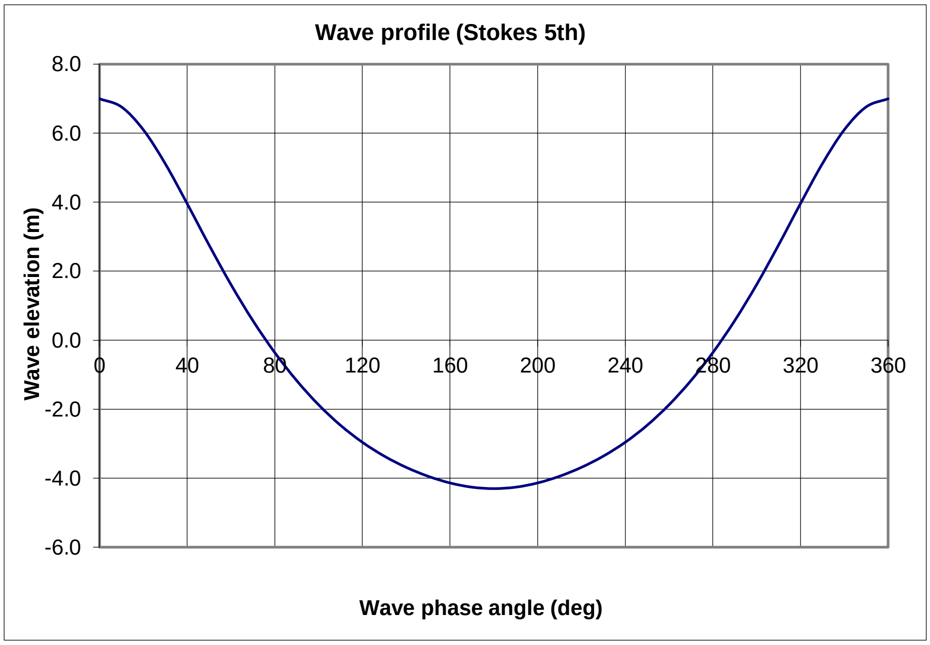
Wave profile h(t)

$$\eta(t)=\frac{L}{2\cdot\pi}\left\{\lambda\cdot\cos(\varphi)+\left(\lambda^2\cdot B_{22}+\lambda^4\cdot B_{24}\right)\cdot\cos(2\varphi)+\left(\lambda^3\cdot B_{33}+\lambda^5\cdot B_{35}\right)\cdot\cos(3\varphi)+\lambda^4\cdot B_{44}\cdot\cos(4\varphi)+\lambda^5\cdot B_{55}\cdot\cos(5\varphi)\right\}$$

ϕ (deg.)	η(t) (m)
0.00	6.9973
10.00	6.7621
20.00	6.0982
30.00	5.1161
40.00	3.9585
50.00	2.7589
60.00	1.6122
70.00	0.5679
80.00	-0.3594
90.00	-1.1713
100.00	-1.8724
110.00	-2.4665
120.00	-2.9593
130.00	-3.3614
140.00	-3.6864
150.00	-3.9448
160.00	-4.1385
170.00	-4.2609
180.00	-4.3031
190.00	-4.2609
200.00	-4.1385
210.00	-3.9448
220.00	-3.6864
230.00	-3.3614
240.00	-2.9593
250.00	-2.4665
260.00	-1.8724
270.00	-1.1713
280.00	-0.3594
290.00	0.5679
300.00	1.6122
310.00	2.7589
320.00	3.9585
330.00	5.1161
340.00	6.0982
350.00	6.7621
360.00	6.9973



General data

(adjusted) Drag coefficient, C_D	0.7	-
(adjusted) Lift coefficient, C_L	0.9	-
(adjusted) Inertia coefficient, C_I	3.29	-
Sea water density, ρ_{sw}	1025	kg/m^3
Total OD pipeline, OD_tot	278.7	mm
Angle of attack relative to pipeline axis, wave	90	deg

ϕ [deg]	u_{w_perp} [m/s]	u_{cm_perp} [m/s]	u_{tot_perp} [m/s]	Fd [N/m]	Fl [N/m]
0.00	2.03	0.27	2.30	529.1	680.3
10.00	2.00	0.27	2.27	513.0	659.6
20.00	1.89	0.27	2.16	466.7	600.1
30.00	1.72	0.27	1.99	396.6	509.9
40.00	1.50	0.27	1.77	311.8	400.9
50.00	1.22	0.27	1.49	223.0	286.7
60.00	0.92	0.27	1.19	140.5	180.6
70.00	0.58	0.27	0.85	72.9	93.8
80.00	0.24	0.27	0.51	26.2	33.7
90.00	-0.10	0.27	0.17	2.9	3.8
100.00	-0.43	0.27	-0.16	-2.5	3.2
110.00	-0.73	0.27	-0.47	-21.7	27.8
120.00	-1.01	0.27	-0.74	-55.4	71.2
130.00	-1.26	0.27	-0.99	-97.6	125.5
140.00	-1.46	0.27	-1.19	-142.2	182.9
150.00	-1.62	0.27	-1.35	-183.4	235.8
160.00	-1.74	0.27	-1.47	-216.5	278.3
170.00	-1.81	0.27	-1.54	-237.7	305.6
180.00	-1.84	0.27	-1.57	-245.1	315.1
190.00	-1.81	0.27	-1.54	-237.7	305.6
200.00	-1.74	0.27	-1.47	-216.5	278.3
210.00	-1.62	0.27	-1.35	-183.4	235.8
220.00	-1.46	0.27	-1.19	-142.2	182.9
230.00	-1.26	0.27	-0.99	-97.6	125.5
240.00	-1.01	0.27	-0.74	-55.4	71.2
250.00	-0.73	0.27	-0.47	-21.7	27.8
260.00	-0.43	0.27	-0.16	-2.5	3.2
270.00	-0.10	0.27	0.17	2.9	3.8
280.00	0.24	0.27	0.51	26.2	33.7
290.00	0.58	0.27	0.85	72.9	93.8
300.00	0.92	0.27	1.19	140.5	180.6
310.00	1.22	0.27	1.49	223.0	286.7
320.00	1.50	0.27	1.77	311.8	400.9
330.00	1.72	0.27	1.99	396.6	509.9
340.00	1.89	0.27	2.16	466.7	600.1
350.00	2.00	0.27	2.27	513.0	659.6
360.00	2.03	0.27	2.30	529.1	680.3

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ϕ [deg]	a_{w_h} [m/s^2]	$a_{w\_h\_perp}$ [m/s^2]	Fi [N/m]	Fd+Fi [N/m]	ABS(Fd+Fi) [N/m]
0.00	0.00	0.00	0.0	529.1	529.1
10.00	0.26	0.26	53.8	566.8	566.8
20.00	0.51	0.51	105.2	571.9	571.9
30.00	0.74	0.74	151.8	548.4	548.4
40.00	0.93	0.93	191.6	503.4	503.4
50.00	1.08	1.08	223.2	446.2	446.2
60.00	1.19	1.19	245.6	386.1	386.1
70.00	1.26	1.26	258.5	331.5	331.5
80.00	1.27	1.27	262.1	288.3	288.3
90.00	1.25	1.25	257.0	259.9	259.9
100.00	1.19	1.19	244.1	241.7	241.7
110.00	1.09	1.09	224.8	203.2	203.2
120.00	0.97	0.97	200.3	144.9	144.9
130.00	0.83	0.83	171.7	74.0	74.0
140.00	0.68	0.68	140.1	-2.1	2.1
150.00	0.52	0.52	106.6	-76.8	76.8
160.00	0.35	0.35	71.7	-144.8	144.8
170.00	0.18	0.18	36.0	-201.7	201.7
180.00	0.00	0.00	0.0	-245.1	245.1
190.00	-0.18	-0.18	-36.0	-273.8	273.8
200.00	-0.35	-0.35	-71.7	-288.1	288.1
210.00	-0.52	-0.52	-106.6	-290.0	290.0
220.00	-0.68	-0.68	-140.1	-282.4	282.4
230.00	-0.83	-0.83	-171.7	-269.3	269.3
240.00	-0.97	-0.97	-200.3	-255.6	255.6
250.00	-1.09	-1.09	-224.8	-246.5	246.5
260.00	-1.19	-1.19	-244.1	-246.6	246.6
270.00	-1.25	-1.25	-257.0	-254.0	254.0
280.00	-1.27	-1.27	-262.1	-235.9	235.9
290.00	-1.26	-1.26	-258.5	-185.6	185.6
300.00	-1.19	-1.19	-245.6	-105.2	105.2
310.00	-1.08	-1.08	-223.2	-0.2	0.2
320.00	-0.93	-0.93	-191.6	120.2	120.2
330.00	-0.74	-0.74	-151.8	244.8	244.8
340.00	-0.51	-0.51	-105.2	361.5	361.5
350.00	-0.26	-0.26	-53.8	459.1	459.1
360.00	0.00	0.00	0.0	529.1	529.1

Maximum absolute hydrodynamic force 571.9 N/m

A.4 Wall Thickness Calculation – Buckling and Collapse – Hydrotest

(14 pages)

Project	**:**	**D12-B Detailed Pipeline Design**
Project #	**:**	18004.500
Subject	**:**	Buckling and Collapse
File #	**:**	18004-60-CAL-01504-02-01 - B&C_10in x 12.7mm_hydrotest
Client	**:**	Wintershall Noordzee
Client File #	**:**	D12B-67031002-PL-LA0580-GLOBAL-006

Originator	: PF	Checked	: EvW
Date	: 10.07.2018		
Revision	: 01		

Buckling and Collapse - 10in x 12.7mm - Hydrotest

Situation

3 Hydrotest

1. Installation: empty
2. Installation: filled
3. Hydrotest
4. Operational

	Pressure (barg)	Temperature (deg. C)
Installation (P_{in}, T_{in})	2	15
Design (P_d, T_d)	148	65
Hydrotest (P_t, T_t)	202	15

Pipeline properties

Nominal diameter		OD_{nom} =	10"	
Nominal diameter		OD_{nom} =	273.1	mm
Nominal wall thickness		d_{nom} =	12.7	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	4.45	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	4.45	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	277.545	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	268.655	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.016	-
Cross sectional area of steel		A =	10389	mm^2
Moment of Inertia		I =	88271060	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	5.5	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	9.0	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	264.1	mm

Piggyback

Nominal diameter	$OD_{nom,p}$ =	0	mm
Nominal wall thickness	$d_{nom,p}$ =	0.0	mm

Coating data

Thickness line pipe	=	2.8	mm
Thickness piggyback	=	0	mm
Density	=	900	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Project	**:**	**D12-B Detailed Pipeline Design**
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Client	**:**	Wintershall Noordzee
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Originator	: PF	Checked	: EvW
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Material			=	L360NB	
Design temperature		T_d	=	15	°C
Yield at ambient temperature		R_e	=	360.00	N/mm^2
Yield at design temperature		R_{ed}	=	360.00	N/mm^2
Density		ρ_{st}	=	7850	kg/m^3
Youngs modulus		E_s	=	210000	N/mm^2
Poisson's ratio		u	=	0.3	-
Linear thermal expansion coefficient		a	=	1.16E-05	$m/m/^oC$
Contents					
Sea water density				1025	kg/m^3
Pipeline product density				0.1	kg/m^3
Pipeline content density used for this case:	Hydrotest			1025	kg/m^3
Pipeline Weights					
Pipeline weight in air	$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$	$W_{pl,a}$	=	1306.1	N/m
Piggyback weight in air		$W_{pg,a}$	=	0.0	N/m
Buoyancy force pipeline	$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$	$F_{B,pl}$	=	613.4	N/m
Buoyancy force piggyback		$F_{B,pb}$	=	0.0	N/m
Submerged pipeline weight,empty		$W_{pl,s,e}$	=	208.1	N/m
Submerged piggyback weight		$W_{pg,s}$	=	0.0	N/m
Total submerged bundle weight,empty		$W_{T,s,e}$	=	208.1	N/m
Total submerged bundle weight,water filled		$W_{T,s,f}$	=	692.6	N/m
Soil					
Submerged density		ρ_{ss}	=	1000	kg/m^3
Depth of burial		d_b	=	0.80	m
Soil cover pressure	$SC_{pres} = r_{ss} \times d_b \times g$	SC_{pres}	=	0.008	N/mm^2
Environmental conditions					
Water depths:					
Seawater density		ρ_{sw}	=	1025	kg/m3
Maximum water depth		WD_{max}	=	40	m LAT
Minimum water depth		WD_{min}	=	28.6	m LAT
Other water depth (to be used for calculations)		WD	=	28.6	m LAT
Storm surge, RP1 yr		ss_{1yr}	=	-0.85	m LAT
Storm surge, RP100 yr		ss_{100yr}	=	-1.24	m LAT
Storm surge water level	SSWL = WD + ss	SSWL	=	27.75	m LAT
Highest Astronomical Tide		HAT	=	2.29	m
Waves (H_{max} & T_{max}): from SW direction (bearing 140 deg)					
Maximum wave height, RP1 yr - installation/hydrotes		$H_{max,1}$	=	11.3	m
Associated maximum wave period, RP1 yr		$T_{ass,1}$	=	9.7	s
Maximum wave height, RP100 yr - operational		$H_{max,100}$	=	16.2	m
Associated maximum wave period, RP100 yr		$T_{ass,100}$	=	11.7	s

Project	**: D12-B Detailed Pipeline Design**
Project #	: 18004.500
Subject	: Buckling and Collapse
File #	: 18004-60-CAL-01504-02-01 - B&C_10in x 12.7mm_hydrotest
Client	: Wintershall Noordzee
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Originator	: PF	Checked	: EvW
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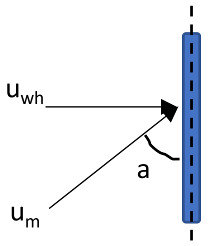
Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$\frac{H_{max}}{g \cdot T_z^2} =$ 0.0122

$\frac{SWL}{g \cdot T_z^2} =$ 0.0301



Wave theory selected:				
1. Airy/linear wave; 2. Stokes 5th		2	Stokes 5th	
Maximum wave particle velocity		u_{wm} =	2.26	m/s
Angle of attack relative to pipeline axis		α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L		u_{wh} =	2.26	m/s
Current:				
Height above seabed at which velocity is known		z* =	0.286	m
Spring tide		u_{st} =	0	m/s
Storm surge, RP1 yr		$u_{ss,1}$ =	0.31	m/s
Storm surge, RP10 yr		$u_{ss,10}$ =	0.33	m/s
Storm surge, RP100 yr		$u_{ss,100}$ =	0.36	m/s
Current velocity at reference height		U_{czr} =	0.31	m/s
Angle of attack relative to pipeline axis		α_{uc} =	90	deg
Horizontal current velocity ⊥ to P/L	$\frac{7}{8} \cdot U_{czr} \cdot \left(\frac{OD_{nom}}{z_r}\right)^{1/7} \cdot \sin(\alpha_{uc}) =$	u_{ch} =	0.27	m/s
Hydrodynamic coefficients:				
Drag coefficient		C_D =	0.7	-
Lift coefficient		C_L =	0.9	-
Inertia coefficient		C_I =	3.29	-
Maximum absolute hydrodynamic force			678	N/m
Temperatures:				
Ambient temperature		T_{amb} =	4	deg. C

Collapse - external pressure only (K.3.3.5.1)

External implosion pipe collapse pressure (P_c) given by: $$(p_c - p_e)\cdot(p_c^2 - p_p^2) = p_c \cdot p_e \cdot p_p \cdot 2 \cdot \delta_o \cdot \frac{OD_g}{d_{nom}}$$

External elastical pipe collapse pressure (P_e):	$P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3$	=	51.3	N/mm^2
External plastic pipe collapse pressure (P_p)	$P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$	=	33.5	N/mm^2
External implosion pipe collapse pressure (P_c):		P_c =	19.8	N/mm^2
Maximum water column above mudline (WC_{max})	$WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT$	=	50.39	m
			0.5039	N/mm^2
Actual external pressure (P_L)	$WC_{max} + SC_{pres}$	=	0.51	N/mm^2

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Assessment: $\gamma_{g,p} \cdot P_L \le \dfrac{\gamma_M \cdot P_c}{\gamma_{m,p}}$ **Where,**

Table 4 - NEN3656

$g_{g,p}$ = 1.05 -
g_M = 0.93 -
$g_{m,p}$ = 1.45 -

Assessment: $\gamma_{g,p} \cdot P_L \le \dfrac{\gamma_M \cdot P_c}{\gamma_{m,p}}$ = **OK**

Collapse - bending moment only (K.3.3.5.2)

Buckling bending moment (M_c) $M_c = D_g^2 d_n R_e$ = 3.2E+08 N·mm

Assessment: $\gamma_{g,M} \times M_L \le \dfrac{\gamma_M \times M_c}{\gamma_{m,M}}$ **Where,**

Table 4 - NEN3656

$g_{g,M}$ = 1.1 -
g_M = 1 -
$g_{m,M}$ = 1.3 -

Maximum allowable bending moment ($M_{L,b}$) $M_{L,b}$ = 2.2E+08 N·mm
= 2.230E+05 N·m

Collapse - external pressure + bending moment only (K.3.3.5.3)

Assessment: $\dfrac{\gamma_{g,p} \times P_L}{P_c / \gamma_{m,p}} + \left(\dfrac{\gamma_{g,M} \times M_L}{M_c / \gamma_{m,M}}\right)^n \le \gamma_M$ **Where,**

Table 4 - NEN3656

$g_{g,p}$ = 1.05 -
$g_{g,M}$ = 1.55 -
$g_{m,p}$ = 1.25 -
$g_{m,M}$ = 1.15 -
g_M = 0.93 -
n = 1 + 300 · d_{nom} / OD_g n = 15.4 -

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.6E+08 N·mm
= 1.57E+05 N·m

Determination maximum span length due to bending only or bending & external pressure

Assessment: $M_{L,m} = \dfrac{q \cdot L^2}{10}$ **Where,**

q = load acting on pipe
L = span length

$$q = \sqrt{\gamma_W{}^2 \cdot W_S{}^2 + \gamma_H{}^2 \cdot (F_D + F_I)^2}$$

Ws = submerged pipeline weight; Ws = 693 N/m
$F_D + F_I$ = 678 N/m
g_w = 1.1 -
g_h = 1.2 -
Table 3 - NEN3656
q = 1114 N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.57E+05 N·m

Maximum span length, L_{max} = 37.6 m

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Progressive plastic collapse (K.3.3.6)

Assessment: $\varepsilon_{max} = \alpha \times \Delta T \leq \left[\frac{R_e(\theta)}{E} \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_p}{R_e(\theta)}\right)^2} + \frac{R_e}{E} \sqrt{0,9 - \frac{3}{4}\left(\frac{\sigma_p}{R_e}\right)^2} \right]$

Temperature difference with ambient; DT =	11	-
R_e =	360.00	N/mm^2
R_{ed} =	360.00	N/mm^2

$$\sigma_p = \frac{p \cdot (OD_{nom} - d_{min})}{2 \cdot d_{min}}$$

s_p = 296.3 N/mm^2

$$\varepsilon_{max} = \alpha \times \Delta T \leq \left[\frac{R_e(\theta)}{E} \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_p}{R_e(\theta)}\right)^2} + \frac{R_e}{E} \sqrt{0,9 - \frac{3}{4}\left(\frac{\sigma_p}{R_e}\right)^2} \right]$$

Assessment: 0.0001 < 0.0023 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 20.8 **OK**

Bar buckling:

Assessment: $L_{max,bb} = \sqrt{4 \cdot \pi^2 \frac{E \cdot I}{|N|}}$

Effective axial force $N = A \cdot (\nu \cdot S_h - \gamma_t \cdot E \cdot \alpha \cdot \Delta T)$

$S_h = g_p \cdot s_h$ — Table 3 - NEN3656 - BC4

g_p =	1.15	-
g_t =	1.1	-
N =	7.56E+05	N

$L_{max,bb}$ = No compressive force m

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Stokes 5th order wave theory

Water depth	WD =	28.6	m (LAT)
Storm surge	ss =	-0.85	m
Storm surge water level	$SWL = WD + ss$ =	27.75	m
Wave height	H =	12	m
Wave period	T =	10.1	s
Grav. Acceleration	g =	9.81	m/s^2
Deep water wave length	$L_o = \frac{g \cdot T^2}{2 \cdot \pi}$ =	159.3	m

Solving for wave length (L) and λ

$$\frac{\pi \cdot H}{SWL} - \frac{L}{SWL}\left\{\lambda + \lambda^3 \cdot B_{33} + \lambda^5 \cdot (B_{35} + B_{55})\right\} = 0 \quad (I)$$

$$\frac{SWL}{L_O} - \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) \cdot \left\{1 + \lambda^2 \cdot C_1 + \lambda^4 \cdot C_2\right\} = 0 \quad (II)$$

Choosing L and solving for λ in (II) results in 4 roots for λ

Estimate actual wave length, L = **147.091 m**

$$A = SWL / L_O = 0.1742$$

$$B = \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) = 0.1564$$

$$\lambda = \pm\sqrt{X}$$

$$X = \frac{-C_1 \cdot B \pm \sqrt{D}}{2 \cdot C_2 \cdot B}$$

$$D = (C_1 \cdot B)^2 - 4 \cdot (C_2 \cdot B) \cdot (-(A - B)) = 0.1403$$

	-	eq. (I)	eq. (II)
λ1	0.236	0.0001	0.0000
λ2	Numerator of X < 0		
λ3	-0.236	2.7169	0.0000
λ4	Numerator of X < 0		

Item	Formula	Value	Unit
s	$s = \sinh\left(\frac{2\cdot\pi\cdot WL}{L}\right) =$	1.4831	-
c	$c = \cosh\left(\frac{2\cdot\pi\cdot WL}{L}\right) =$	1.7888	-
A11	$A_{11} = \frac{1}{s} =$	0.6742	-
A13	$A_{13} = \frac{-c^2\cdot(5\cdot c^2+1)}{8\cdot s^5} =$	-0.9474	-
	$A_{15} = -\frac{1184\cdot c^{10} - 1440\cdot c^8 - 1992\cdot c^6 + 2641\cdot c^4 - 249\cdot c^2 + 18}{1536\cdot s^{11}} =$	-1.7657	-
A22	$A_{22} = \frac{3}{8\cdot s^4} =$	0.0775	-
A24	$A_{24} = \frac{192\cdot c^8 - 424\cdot c^6 - 312\cdot c^4 + 480\cdot c^2 - 17}{768\cdot s^{10}} =$	0.1153	-
A33	$A_{33} = \frac{13 - 4\cdot c^2}{64\cdot s^7} =$	0.0002	-
	$A_{35} = \frac{512\cdot c^{12} + 4224\cdot c^{10} - 6800\cdot c^8 - 12808\cdot c^6 + 16704\cdot c^4 - 3154\cdot c^2 - 107}{4096\cdot s^{13}\cdot(6\cdot c^2 - 1)} =$	0.0794	-
A44	$A_{44} = \frac{80\cdot c^6 - 816\cdot c^4 + 1338\cdot c^2 - 197}{1536\cdot s^{10}\cdot(6\cdot c^2 - 1)} =$	-0.0011	-

$$A_{55} = -\frac{2880 \cdot c^{10} - 72480 \cdot c^8 + 324000 \cdot c^6 - 432000 \cdot c^4 + 163470 \cdot c^2 - 16245}{61440 \cdot s^{11} \cdot (6 \cdot c^2 - 1) \cdot (8 \cdot c^4 - 11 \cdot c^2 + 3)} =$$ 0.0000 -

B22 $$B_{22} = \frac{(2 \cdot c^2 + 1) \cdot c}{4 \cdot s^3} =$$ 1.0142 -

B24 $$B_{24} = \frac{c \cdot (272 \cdot c^8 - 504 \cdot c^6 - 192 \cdot c^4 + 322 \cdot c^2 + 21)}{384 \cdot s^9} =$$ 1.4871 -

B33 $$B_{33} = \frac{3 \cdot (8 \cdot c^6 + 1)}{64 \cdot s^6} =$$ 1.1586 -

$$B_{35} = \frac{88128 \cdot c^{14} - 208224 \cdot c^{12} + 70848 \cdot c^{10} + 54000 \cdot c^8 - 21816 \cdot c^6 + 6264 \cdot c^4 - 54 \cdot c^2 - 81}{12288 \cdot s^{12} \cdot (6 \cdot c^2 - 1)} =$$ = 4.2602 -

B44 $$B_{44} = c \cdot \frac{768 \cdot c^{10} - 488 \cdot c^8 - 48 \cdot c^6 + 48 \cdot c^4 + 106 \cdot c^2 - 21}{384 \cdot s^9 \cdot (6 \cdot c^2 - 1)} =$$ 1.5160 -

$$B_{55} = \frac{192000 \cdot c^{16} - 26720 \cdot c^{14} + 83680 \cdot c^{12} + 20160 \cdot c^{10} - 7280 \cdot c^8 + 7160 \cdot c^6 - 1800 \cdot c^4 - 1050 \cdot c^2 + 225}{12288 \cdot s^{10} \cdot (8 \cdot c^4 - 11 \cdot c^2 + 3) \cdot (6 \cdot c^2 - 1)} =$$ = 2.2768 -

C1 $$C_1 = \frac{8 \cdot c^4 - 8 \cdot c^2 + 9}{8 \cdot s^4} =$$ 1.6871 -

$$C_2 = \frac{3840 \cdot c^{12} - 4096 \cdot c^{10} + 2592 \cdot c^8 - 1008 \cdot c^6 + 5944 \cdot c^4 - 1830 \cdot c^2 + 147}{512 \cdot s^{10} \cdot (6 \cdot c^2 - 1)} =$$ 6.3370 -

C3 $$C_3 = -\frac{1}{4 \cdot c \cdot s} =$$ -0.0942 -

C4 $$C_4 = \frac{12 \cdot c^8 + 36 \cdot c^6 - 162 \cdot c^4 + 141 \cdot c^2 - 27}{192 \cdot c \cdot s^9} =$$ 0.1008 -

K1 $$K_1 = \lambda \cdot A_{11} + \lambda^3 \cdot A_{13} + \lambda^5 \cdot A_{15} =$$ 0.1455 -

K2	$K_2 = \lambda^2 \cdot A_{22} + \lambda^4 \cdot A_{24} =$	0.0047	-
K3	$K_3 = \lambda^3 \cdot A_{33} + \lambda^5 \cdot A_{35} =$	0.0001	-
K4	$K_4 = \lambda^4 \cdot A_{44} =$	0.0000	-
K5	$K_5 = \lambda^5 \cdot A_{55} =$	0.0000	-

Horizontal wave particle velocities

Water depth at which data required, z (w.r.t. seabed) 0.2731 m

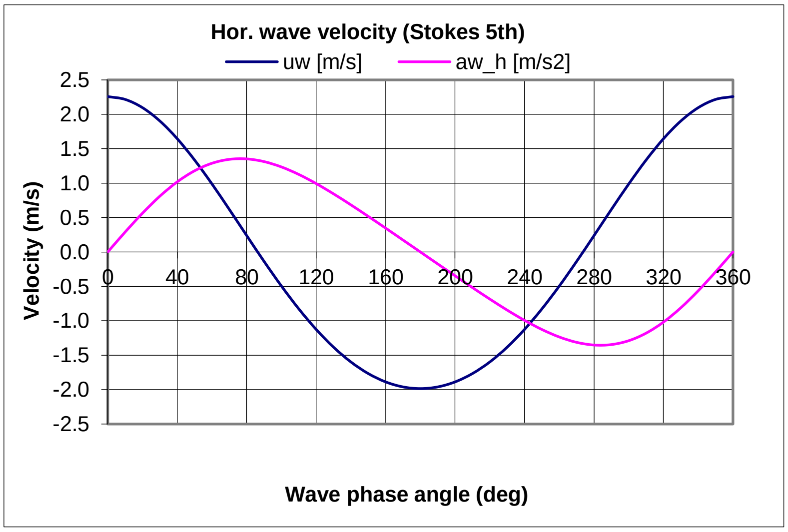
Horizontal velocity, u_w

$$u_w = \frac{L}{T} \cdot \sum_{n=1}^{5} n \cdot K_n \cdot \cosh\left(n \cdot \frac{2 \cdot \pi}{L} \cdot z\right) \cdot \cos(n \cdot \varphi)$$

Horizontal acceleration, $a_{w,h}$

$$a_{w,h} = \frac{2 \cdot \pi \cdot L}{T^2} \cdot \sum_{n=1}^{5} n^2 \cdot K_n \cdot \cosh\left(n \cdot \frac{2 \cdot \pi}{L} \cdot z\right) \cdot \sin(n \cdot \varphi)$$

ϕ [deg.]	uw [m/s]	aw_h [m/s^2]
0.00	2.2577	0.0000
10.00	2.2169	0.2891
20.00	2.0968	0.5637
30.00	1.9032	0.8106
40.00	1.6456	1.0186
50.00	1.3361	1.1795
60.00	0.9886	1.2890
70.00	0.6178	1.3457
80.00	0.2382	1.3521
90.00	-0.1366	1.3131
100.00	-0.4949	1.2354
110.00	-0.8269	1.1265
120.00	-1.1248	0.9940
130.00	-1.3831	0.8449
140.00	-1.5979	0.6846
150.00	-1.7666	0.5175
160.00	-1.8879	0.3465
170.00	-1.9609	0.1736
180.00	-1.9852	0.0000
190.00	-1.9609	-0.1736
200.00	-1.8879	-0.3465



210.00	-1.7666	-0.5175
220.00	-1.5979	-0.6846
230.00	-1.3831	-0.8449
240.00	-1.1248	-0.9940
250.00	-0.8269	-1.1265
260.00	-0.4949	-1.2354
270.00	-0.1366	-1.3131
280.00	0.2382	-1.3521
290.00	0.6178	-1.3457
300.00	0.9886	-1.2890
310.00	1.3361	-1.1795
320.00	1.6456	-1.0186
330.00	1.9032	-0.8106
340.00	2.0968	-0.5637
350.00	2.2169	-0.2891
360.00	2.2577	0.0000

U_{wm} = max. wave particle velocity = 2.26 m/s

Originator	: PF	Checked	: EvW
Date	: 10.07.2018		
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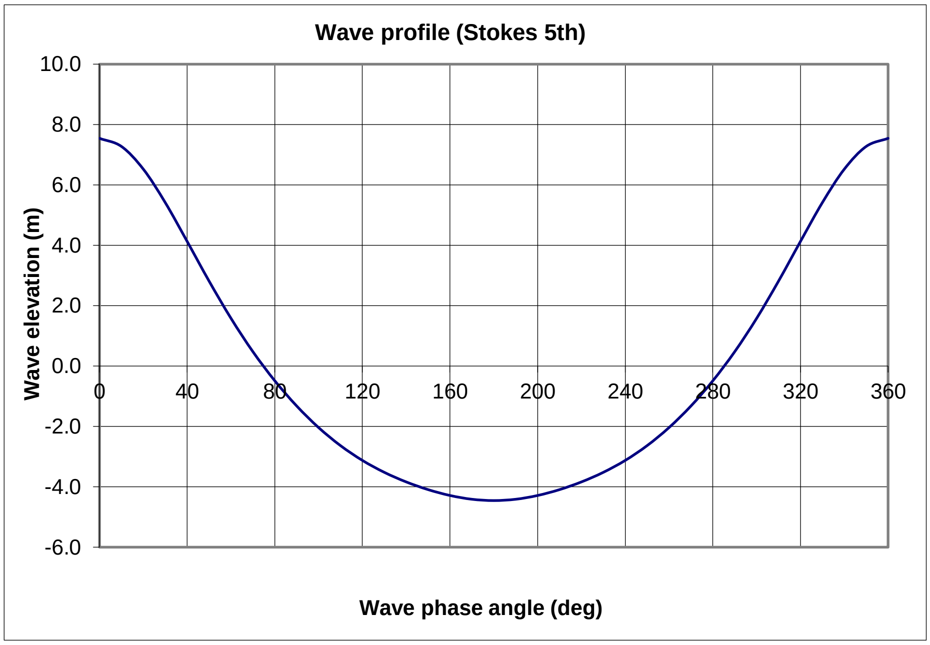
Wave profile h(t)

$$\eta(t)=\frac{L}{2\cdot\pi}\left\{\lambda\cdot\cos(\varphi)+\left(\lambda^2\cdot B_{22}+\lambda^4\cdot B_{24}\right)\cdot\cos(2\varphi)+\left(\lambda^3\cdot B_{33}+\lambda^5\cdot B_{35}\right)\cdot\cos(3\varphi)+\lambda^4\cdot B_{44}\cdot\cos(4\varphi)+\lambda^5\cdot B_{55}\cdot\cos(5\varphi)\right\}$$

ϕ (deg.)	η(t) (m)
0.00	7.5431
10.00	7.2751
20.00	6.5217
30.00	5.4161
40.00	4.1287
50.00	2.8152
60.00	1.5819
70.00	0.4782
80.00	-0.4872
90.00	-1.3226
100.00	-2.0369
110.00	-2.6354
120.00	-3.1254
130.00	-3.5206
140.00	-3.8387
150.00	-4.0935
160.00	-4.2877
170.00	-4.4125
180.00	-4.4560
190.00	-4.4125
200.00	-4.2877
210.00	-4.0935
220.00	-3.8387
230.00	-3.5206
240.00	-3.1254
250.00	-2.6354
260.00	-2.0369
270.00	-1.3226
280.00	-0.4872
290.00	0.4782
300.00	1.5819
310.00	2.8152
320.00	4.1287
330.00	5.4161
340.00	6.5217
350.00	7.2751
360.00	7.5431



Originator	: PF	Checked	: EvW
Date	: 10.07.2018		
Revision	: 01		

General data

(adjusted) Drag coefficient, C_D	0.7	-
(adjusted) Lift coefficient, C_L	0.9	-
(adjusted) Inertia coefficient, C_I	3.29	-
Sea water density, ρ_{sw}	1025	kg/m^3
Total OD pipeline, OD_tot	278.7	mm
Angle of attack relative to pipeline axis, wave	90	deg

ϕ [deg]	u_{w_perp} [m/s]	u_{cm_perp} [m/s]	u_{tot_perp} [m/s]	Fd [N/m]	Fl [N/m]
0.00	2.26	0.27	2.53	638.5	821.0
10.00	2.22	0.27	2.49	618.1	794.7
20.00	2.10	0.27	2.37	559.8	719.8
30.00	1.90	0.27	2.17	472.0	606.8
40.00	1.65	0.27	1.92	366.7	471.5
50.00	1.34	0.27	1.61	257.7	331.4
60.00	0.99	0.27	1.26	158.2	203.5
70.00	0.62	0.27	0.89	78.7	101.2
80.00	0.24	0.27	0.51	25.8	33.1
90.00	-0.14	0.27	0.13	1.8	2.3
100.00	-0.49	0.27	-0.23	-5.1	6.5
110.00	-0.83	0.27	-0.56	-31.1	39.9
120.00	-1.12	0.27	-0.86	-73.2	94.1
130.00	-1.38	0.27	-1.11	-124.0	159.4
140.00	-1.60	0.27	-1.33	-176.4	226.8
150.00	-1.77	0.27	-1.50	-224.1	288.1
160.00	-1.89	0.27	-1.62	-261.9	336.7
170.00	-1.96	0.27	-1.69	-286.0	367.8
180.00	-1.99	0.27	-1.72	-294.3	378.4
190.00	-1.96	0.27	-1.69	-286.0	367.8
200.00	-1.89	0.27	-1.62	-261.9	336.7
210.00	-1.77	0.27	-1.50	-224.1	288.1
220.00	-1.60	0.27	-1.33	-176.4	226.8
230.00	-1.38	0.27	-1.11	-124.0	159.4
240.00	-1.12	0.27	-0.86	-73.2	94.1
250.00	-0.83	0.27	-0.56	-31.1	39.9
260.00	-0.49	0.27	-0.23	-5.1	6.5
270.00	-0.14	0.27	0.13	1.8	2.3
280.00	0.24	0.27	0.51	25.8	33.1
290.00	0.62	0.27	0.89	78.7	101.2
300.00	0.99	0.27	1.26	158.2	203.5
310.00	1.34	0.27	1.61	257.7	331.4
320.00	1.65	0.27	1.92	366.7	471.5
330.00	1.90	0.27	2.17	472.0	606.8
340.00	2.10	0.27	2.37	559.8	719.8
350.00	2.22	0.27	2.49	618.1	794.7
360.00	2.26	0.27	2.53	638.5	821.0

Originator : PF
Date : 10.07.2018
Revision : 01
Checked : EvW

ϕ [deg]	a_{w_h} [m/s^2]	$a_{w\_h\_perp}$ [m/s^2]	Fi [N/m]	Fd+Fi [N/m]	ABS(Fd+Fi) [N/m]
0.00	0.00	0.00	0.0	638.5	638.5
10.00	0.29	0.29	59.5	677.6	677.6
20.00	0.56	0.56	116.0	675.8	675.8
30.00	0.81	0.81	166.8	638.7	638.7
40.00	1.02	1.02	209.5	576.2	576.2
50.00	1.18	1.18	242.7	500.4	500.4
60.00	1.29	1.29	265.2	423.4	423.4
70.00	1.35	1.35	276.8	355.6	355.6
80.00	1.35	1.35	278.2	303.9	303.9
90.00	1.31	1.31	270.1	271.9	271.9
100.00	1.24	1.24	254.1	249.1	249.1
110.00	1.13	1.13	231.7	200.7	200.7
120.00	0.99	0.99	204.5	131.3	131.3
130.00	0.84	0.84	173.8	49.8	49.8
140.00	0.68	0.68	140.8	-35.6	35.6
150.00	0.52	0.52	106.5	-117.6	117.6
160.00	0.35	0.35	71.3	-190.6	190.6
170.00	0.17	0.17	35.7	-250.3	250.3
180.00	0.00	0.00	0.0	-294.3	294.3
190.00	-0.17	-0.17	-35.7	-321.8	321.8
200.00	-0.35	-0.35	-71.3	-333.2	333.2
210.00	-0.52	-0.52	-106.5	-330.6	330.6
220.00	-0.68	-0.68	-140.8	-317.3	317.3
230.00	-0.84	-0.84	-173.8	-297.8	297.8
240.00	-0.99	-0.99	-204.5	-277.7	277.7
250.00	-1.13	-1.13	-231.7	-262.8	262.8
260.00	-1.24	-1.24	-254.1	-259.2	259.2
270.00	-1.31	-1.31	-270.1	-268.4	268.4
280.00	-1.35	-1.35	-278.2	-252.4	252.4
290.00	-1.35	-1.35	-276.8	-198.1	198.1
300.00	-1.29	-1.29	-265.2	-106.9	106.9
310.00	-1.18	-1.18	-242.7	15.1	15.1
320.00	-1.02	-1.02	-209.5	157.2	157.2
330.00	-0.81	-0.81	-166.8	305.2	305.2
340.00	-0.56	-0.56	-116.0	443.9	443.9
350.00	-0.29	-0.29	-59.5	558.6	558.6
360.00	0.00	0.00	0.0	638.5	638.5

Maximum absolute hydrodynamic force 677.6 N/m

A.5 Wall Thickness Calculation – Buckling and Collapse – Operation

(14 pages)

Project	**:**	**D12-B Detailed Pipeline Design**
Project #	**:**	18004.500
Subject	**:**	Buckling and Collapse
File #	**:**	18004-60-CAL-01504-03-01 - B&C_10in x 12.7mm_operation
Client	**:**	Wintershall Noordzee
Client File #	**:**	D12B-67031002-PL-LA0580-GLOBAL-007

Originator	: PF	Checked	:
Date	: 10.07.2018		
Revision	: 01		

Buckling and Collapse - 10in x 12.7mm - Operational

Situation

4
Operational

1. Installation: empty
2. Installation: filled
3. Hydrotest
4. Operational

	Pressure (barg)	Temperature (deg. C)
Installation (P_{in}, T_{in})	2	15
Design (P_d, T_d)	148	65
Hydrotest (P_t, T_t)	202	15

Pipeline properties

Nominal diameter		OD_{nom} =	10"	
Nominal diameter		OD_{nom} =	273.1	mm
Nominal wall thickness		d_{nom} =	12.7	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	4.45	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	4.45	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	277.545	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	268.655	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.016	-
Cross sectional area of steel		A =	10389	mm^2
Moment of Inertia		I =	88271060	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	5.5	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	9.0	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	264.1	mm

Piggyback

Nominal diameter	$OD_{nom,p}$ =	0	mm
Nominal wall thickness	$d_{nom,p}$ =	0.0	mm

Coating data

Thickness line pipe	=	2.8	mm
Thickness piggyback	=	0	mm
Density	=	900	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Material

Material		=	L360NB	
Design temperature	T_d	=	65	°C
Yield at ambient temperature	R_e	=	360.00	N/mm^2
Yield at design temperature	R_{ed}	=	343.20	N/mm^2
Density	ρ_{st}	=	7850	kg/m^3
Youngs modulus	E_s	=	210000	N/mm^2
Poisson's ratio	u	=	0.3	-
Linear thermal expansion coefficient	a	=	1.16E-05	$m/m/^oC$

Contents

Sea water density		1025	kg/m^3
Pipeline product density		0.1	kg/m^3
Pipeline content density used for this case:	Operational	0.1	kg/m^3

Pipeline Weights

$$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$$

Pipeline weight in air	$W_{pl,a}$	=	821.6	N/m
Piggyback weight in air	$W_{pg,a}$	=	0.0	N/m

$$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$$

Buoyancy force pipeline	$F_{B,pl}$	=	613.4	N/m
Buoyancy force piggyback	$F_{B,pb}$	=	0.0	N/m
Submerged pipeline weight,empty	$W_{pl,s,e}$	=	208.1	N/m
Submerged piggyback weight	$W_{pg,s}$	=	0.0	N/m
Total submerged bundle weight,empty	$W_{T,s,e}$	=	208.1	N/m
Total submerged bundle weight,water filled	$W_{T,s,f}$	=	692.6	N/m

Soil

Submerged density		ρ_{ss}	=	1000	kg/m^3
Depth of burial		d_b	=	0.80	m
Soil cover pressure	$SC_{pres} = r_{ss} \times d_b \times g$	SC_{pres}	=	0.008	N/mm^2

Environmental conditions

Water depths:

Seawater density		ρ_{sw}	=	1025	kg/m3
Maximum water depth		WD_{max}	=	40	m LAT
Minimum water depth		WD_{min}	=	28.6	m LAT
Other water depth (to be used for calculations)		WD	=	28.6	m LAT
Storm surge, RP1 yr		ss_{1yr}	=	-0.85	m LAT
Storm surge, RP100 yr		ss_{100yr}	=	-1.24	m LAT
Storm surge water level	SSWL = WD + ss	SSWL	=	27.36	m LAT
Highest Astronomical Tide		HAT	=	2.29	m

Waves (H_{max} & T_{max}): *from SW direction (bearing 140 deg)*

Maximum wave height, RP1 yr - installation/hydrotes	$H_{max,1}$	=	11.3	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$	=	9.7	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$	=	16.2	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$	=	11.7	s

Project	**:**	**D12-B Detailed Pipeline Design**
Project #	**:**	18004.500
Subject	**:**	Buckling and Collapse
File #	**:**	18004-60-CAL-01504-03-01 - B&C_10in x 12.7mm_operation
Client	**:**	Wintershall Noordzee
Client File #	**:**	D12B-67031002-PL-LA0580-GLOBAL-007

Originator	: PF	Checked	:
Date	: 10.07.2018		
Revision	: 01		

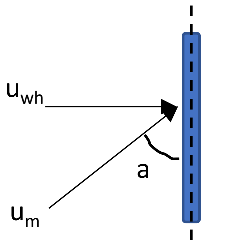
Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$$\frac{H_{max}}{g \cdot T_z^2} = 0.0121$$

$$\frac{SWL}{g \cdot T_z^2} = 0.0204$$

Wave theory selected:

1. Airy/linear wave; 2. Stokes 5th — **2** — Stokes 5th



Maximum wave particle velocity	u_{wm} =	3.51	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	3.51	m/s

Current:

Height above seabed at which velocity is known	z^* =	0.286	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.31	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.33	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	0.36	m/s
Current velocity at reference height	U_{czr} =	0.36	m/s
Angle of attack relative to pipeline axis	α_{uc} =	90	deg
Horizontal current velocity ⊥ to P/L $\frac{7}{8} \cdot U_{czr} \cdot \left(\frac{OD_{nom}}{z_r}\right)^{1/7} \cdot \sin(\alpha_{uc}) =$	u_{ch} =	0.31	m/s

Hydrodynamic coefficients:

Drag coefficient	C_D =	0.7	-
Lift coefficient	C_L =	0.9	-
Inertia coefficient	C_I =	3.29	-

Maximum absolute hydrodynamic force 1503 N/m

Temperatures:

Ambient temperature T_{amb} = 4 deg. C

Collapse - external pressure only (K.3.3.5.1)

External implosion pipe collapse pressure (P_c) given by:

$$(p_c - p_e) \cdot \left(p_c^2 - p_p^2\right) = p_c \cdot p_e \cdot p_p \cdot 2 \cdot \delta_o \cdot \frac{OD_g}{d_{nom}}$$

External elastical pipe collapse pressure (P_e): $P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3$ = 51.3 N/mm²

External plastic pipe collapse pressure (P_p) $P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$ = 33.5 N/mm²

External implosion pipe collapse pressure (P_c): P_c = 19.8 N/mm²

Maximum water column above mudline (WC_{max}) $WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT$ = 50.39 m

0.5039 N/mm²

Actual external pressure (P_L) $WC_{max} + SC_{pres}$ = 0.51 N/mm²

Assessment: $\gamma_{g,p} \cdot P_L \le \frac{\gamma_M \cdot P_c}{\gamma_{m,p}}$ **Where,**

Table 4 - NEN3656

$g_{g,p}$ =	1.05	-
g_M =	0.93	-
$g_{m,p}$ =	1.45	-

Assessment: $\gamma_{g,p} \cdot P_L \le \frac{\gamma_M \cdot P_c}{\gamma_{m,p}}$ **= OK**

Collapse - bending moment only (K.3.3.5.2)

Buckling bending moment (M_c) $M_c = D_g^2 d_n R_e$ = 3.2E+08 N·mm

Assessment: $\gamma_{g,M} \times M_L \le \frac{\gamma_M \times M_c}{\gamma_{m,M}}$ **Where,**

Table 4 - NEN3656

$g_{g,M}$ =	1.1	-
g_M =	1	-
$g_{m,M}$ =	1.3	-

Maximum allowable bending moment ($M_{L,b}$) $M_{L,b}$ = 2.2E+08 N·mm
= 2.230E+05 N·m

Collapse - external pressure + bending moment only (K.3.3.5.3)

Assessment: $\frac{\gamma_{g,p} \times P_L}{P_c / \gamma_{m,p}} + \left(\frac{\gamma_{g,M} \times M_L}{M_c / \gamma_{m,M}}\right)^n \le \gamma_M$ **Where,**

Table 4 - NEN3656

$g_{g,p}$ =	1.05	-
$g_{g,M}$ =	1.55	-
$g_{m,p}$ =	1.25	-
$g_{m,M}$ =	1.15	-
g_M =	0.93	-

$n = 1 + 300 \cdot d_{nom} / OD_g$ n = 15.4 -

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.6E+08 N·mm
= 1.57E+05 N·m

Determination maximum span length due to bending only or bending & external pressure

Assessment: $M_{L,m} = \frac{q \cdot L^2}{10}$ **Where,**

q = load acting on pipe
L = span length

$$q = \sqrt{\gamma_W{}^2 \cdot W_S{}^2 + \gamma_H{}^2 \cdot (F_D + F_I)^2}$$

Ws = submerged pipeline weight; Ws = 208 N/m

$F_D + F_I$ =	1503	N/m
g_w =	1.1	-
g_h =	1.2	-

Table 3 - NEN3656

q = 1818 N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.57E+05 N·m

Maximum span length, L_{max} = 29.4 m

Project	**:** **D12-B Detailed Pipeline Design**	
Project #	**:** 18004.500	
Subject	**:** Buckling and Collapse	
File #	**:** 18004-60-CAL-01504-03-01 - B&C_10in x 12.7mm_operation	
Client	**:** Wintershall Noordzee	
Client File #	**:** D12B-67031002-PL-LA0580-GLOBAL-007	

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Progressive plastic collapse (K.3.3.6)

Assessment: $\varepsilon_{max} = \alpha \times \Delta T \leq \left[\frac{R_e(\theta)}{E} \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_p}{R_e(\theta)}\right)^2} + \frac{R_e}{E}\sqrt{0{,}9 - \frac{3}{4}\left(\frac{\sigma_p}{R_e}\right)^2} \right]$

Temperature difference with ambient; DT	=	61	-
R_e	=	360.00	N/mm^2
R_{ed}	=	343.20	N/mm^2

$$\sigma_p = \frac{p \cdot (OD_{nom} - d_{min})}{2 \cdot d_{min}}$$

s_p = 217.1 N/mm^2

$$\varepsilon_{max} = \alpha \times \Delta T \leq \left[\frac{R_e(\theta)}{E} \sqrt{1 - \frac{3}{4}\left(\frac{\sigma_p}{R_e(\theta)}\right)^2} + \frac{R_e}{E}\sqrt{0{,}9 - \frac{3}{4}\left(\frac{\sigma_p}{R_e}\right)^2} \right]$$

Assessment: 0.0007 < 0.0027 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 20.8 **OK**

Bar buckling:

Assessment: $L_{max,bb} = \sqrt{4 \cdot \pi^2 \frac{E \cdot I}{|N|}}$

Effective axial force $N = A \cdot (\nu \cdot S_h - \gamma_t \cdot E \cdot \alpha \cdot \Delta T)$

$S_h = g_p \cdot s_h$ Table 3 - NEN3656 - BC4

g_p	=	1.15	-
g_t	=	1.1	-
N	=	-9.20E+05	N

$L_{max,bb}$ = 28.2 m

Stokes 5th order wave theory

Water depth	WD =	28.6	m (LAT)
Storm surge	ss =	-1.24	m
Storm surge water level	$SWL = WD + ss$ =	27.36	m
Wave height	H =	16.2	m
Wave period	T =	11.7	s
Grav. Acceleration	g =	9.81	m/s^2
Deep water wave length	$L_o = \frac{g \cdot T^2}{2 \cdot \pi}$ =	213.7	m

Solving for wave length (L) and λ

$$\frac{\pi \cdot H}{SWL} - \frac{L}{SWL}\left\{\lambda + \lambda^3 \cdot B_{33} + \lambda^5 \cdot (B_{35} + B_{55})\right\} = 0 \quad (\text{I})$$

$$\frac{SWL}{L_O} - \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) \cdot \left\{1 + \lambda^2 \cdot C_1 + \lambda^4 \cdot C_2\right\} = 0 \quad (\text{II})$$

Choosing L and solving for λ in (II) results in 4 roots for λ

Estimate actual wave length, L **187.732** **m**

$$A = SWL / L_O = 0.1280$$

$$B = \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) = 0.1055$$

$$\lambda = \pm\sqrt{X}$$

$$X = \frac{-C_1 \cdot B \pm \sqrt{D}}{2 \cdot C_2 \cdot B}$$

$$D = (C_1 \cdot B)^2 - 4 \cdot (C_2 \cdot B) \cdot (-(A - B)) = 0.3134$$

	-	eq. (I)	eq. (II)
λ1	0.229	0.0000	0.0000
λ2	Numerator of X < 0		
λ3	-0.229	3.7203	0.0000
λ4	Numerator of X < 0		

Item	Formula	Value	Unit
s	$s = \sinh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.0492	-
c	$c = \cosh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.4494	-
A11	$A_{11} = \frac{1}{s} =$	0.9531	-
A13	$A_{13} = \frac{-c^2 \cdot (5 \cdot c^2 + 1)}{8 \cdot s^5} =$	-2.3764	-
	$A_{15} = -\frac{1184 \cdot c^{10} - 1440 \cdot c^8 - 1992 \cdot c^6 + 2641 \cdot c^4 - 249 \cdot c^2 + 18}{1536 \cdot s^{11}} =$	-5.0225	-
A22	$A_{22} = \frac{3}{8 \cdot s^4} =$	0.3095	-
A24	$A_{24} = \frac{192 \cdot c^8 - 424 \cdot c^6 - 312 \cdot c^4 + 480 \cdot c^2 - 17}{768 \cdot s^{10}} =$	-0.4650	-
A33	$A_{33} = \frac{13 - 4 \cdot c^2}{64 \cdot s^7} =$	0.0513	-
	$A_{35} = \frac{512 \cdot c^{12} + 4224 \cdot c^{10} - 6800 \cdot c^8 - 12808 \cdot c^6 + 16704 \cdot c^4 - 3154 \cdot c^2 - 107}{4096 \cdot s^{13} \cdot (6 \cdot c^2 - 1)} =$	0.3679	-
A44	$A_{44} = \frac{80 \cdot c^6 - 816 \cdot c^4 + 1338 \cdot c^2 - 197}{1536 \cdot s^{10} \cdot (6 \cdot c^2 - 1)} =$	-0.0085	-

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$$A_{55} = -\frac{2880 \cdot c^{10} - 72480 \cdot c^{8} + 324000 \cdot c^{6} - 432000 \cdot c^{4} + 163470 \cdot c^{2} - 16245}{61440 \cdot s^{11} \cdot (6 \cdot c^{2} - 1) \cdot (8 \cdot c^{4} - 11 \cdot c^{2} + 3)} =$$ -0.0071 -

B22 $$B_{22} = \frac{(2 \cdot c^{2} + 1) \cdot c}{4 \cdot s^{3}} =$$ 1.6320 -

B24 $$B_{24} = \frac{c \cdot (272 \cdot c^{8} - 504 \cdot c^{6} - 192 \cdot c^{4} + 322 \cdot c^{2} + 21)}{384 \cdot s^{9}} =$$ 1.1640 -

B33 $$B_{33} = \frac{3 \cdot (8 \cdot c^{6} + 1)}{64 \cdot s^{6}} =$$ 2.6419 -

$$B_{35} = \frac{88128 \cdot c^{14} - 208224 \cdot c^{12} + 70848 \cdot c^{10} + 54000 \cdot c^{8} - 21816 \cdot c^{6} + 6264 \cdot c^{4} - 54 \cdot c^{2} - 81}{12288 \cdot s^{12} \cdot (6 \cdot c^{2} - 1)} =$$
= 7.0611 -

B44 $$B_{44} = c \cdot \frac{768 \cdot c^{10} - 488 \cdot c^{8} - 48 \cdot c^{6} + 48 \cdot c^{4} + 106 \cdot c^{2} - 21}{384 \cdot s^{9} \cdot (6 \cdot c^{2} - 1)} =$$ 4.6219 -

$$B_{55} = \frac{192000 \cdot c^{16} - 26720 \cdot c^{14} + 83680 \cdot c^{12} + 20160 \cdot c^{10} - 7280 \cdot c^{8} + 7160 \cdot c^{6} - 1800 \cdot c^{4} - 1050 \cdot c^{2} + 225}{12288 \cdot s^{10} \cdot (8 \cdot c^{4} - 11 \cdot c^{2} + 3) \cdot (6 \cdot c^{2} - 1)} =$$
= 9.5161 -

C1 $$C_{1} = \frac{8 \cdot c^{4} - 8 \cdot c^{2} + 9}{8 \cdot s^{4}} =$$ 2.8370 -

$$C_{2} = \frac{3840 \cdot c^{12} - 4096 \cdot c^{10} + 2592 \cdot c^{8} - 1008 \cdot c^{6} + 5944 \cdot c^{4} - 1830 \cdot c^{2} + 147}{512 \cdot s^{10} \cdot (6 \cdot c^{2} - 1)} =$$ 23.5534 -

C3 $$C_{3} = -\frac{1}{4 \cdot c \cdot s} =$$ -0.1644 -

C4 $$C_{4} = \frac{12 \cdot c^{8} + 36 \cdot c^{6} - 162 \cdot c^{4} + 141 \cdot c^{2} - 27}{192 \cdot c \cdot s^{9}} =$$ 0.2840 -

K1 $$K_{1} = \lambda \cdot A_{11} + \lambda^{3} \cdot A_{13} + \lambda^{5} \cdot A_{15} =$$ 0.1866 -

K2	$K_2 = \lambda^2 \cdot A_{22} + \lambda^4 \cdot A_{24} =$	0.0149	-
K3	$K_3 = \lambda^3 \cdot A_{33} + \lambda^5 \cdot A_{35} =$	0.0008	-
K4	$K_4 = \lambda^4 \cdot A_{44} =$	0.0000	-
K5	$K_5 = \lambda^5 \cdot A_{55} =$	0.0000	-

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Horizontal wave particle velocities

Water depth at which data required, z (w.r.t. seabed) 0.2731 m

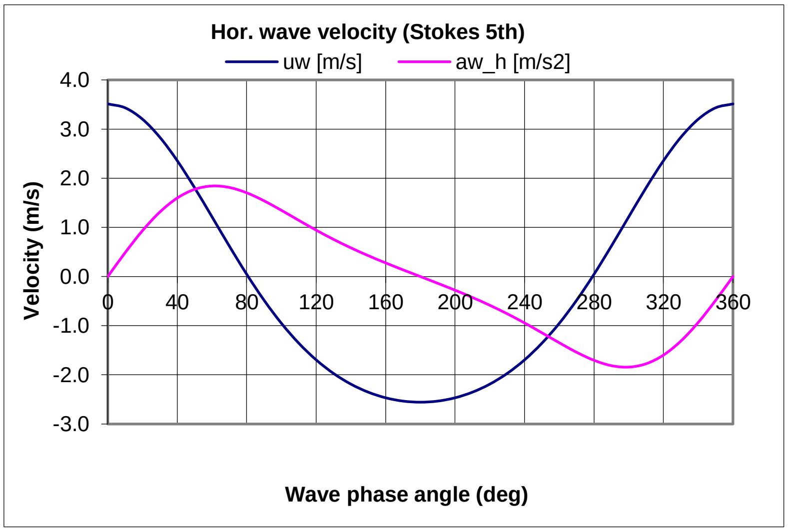
Horizontal velocity, u_w

$$u_w = \frac{L}{T} \cdot \sum_{n=1}^{5} n \cdot K_n \cdot \cosh\left(n \cdot \frac{2 \cdot \pi}{L} \cdot z\right) \cdot \cos(n \cdot \varphi)$$

Horizontal acceleration, $a_{w,h}$

$$a_{w,h} = \frac{2 \cdot \pi \cdot L}{T^2} \cdot \sum_{n=1}^{5} n^2 \cdot K_n \cdot \cosh\left(n \cdot \frac{2 \cdot \pi}{L} \cdot z\right) \cdot \sin(n \cdot \varphi)$$

ϕ [deg.]	uw [m/s]	aw_h [m/s^2]
0.00	3.5121	0.0000
10.00	3.4327	0.4854
20.00	3.2006	0.9339
30.00	2.8333	1.3125
40.00	2.3577	1.5969
50.00	1.8070	1.7738
60.00	1.2166	1.8421
70.00	0.6203	1.8123
80.00	0.0471	1.7039
90.00	-0.4813	1.5408
100.00	-0.9511	1.3472
110.00	-1.3559	1.1435
120.00	-1.6948	0.9440
130.00	-1.9708	0.7567
140.00	-2.1883	0.5842
150.00	-2.3521	0.4256
160.00	-2.4661	0.2778
170.00	-2.5334	0.1371
180.00	-2.5556	0.0000
190.00	-2.5334	-0.1371
200.00	-2.4661	-0.2778



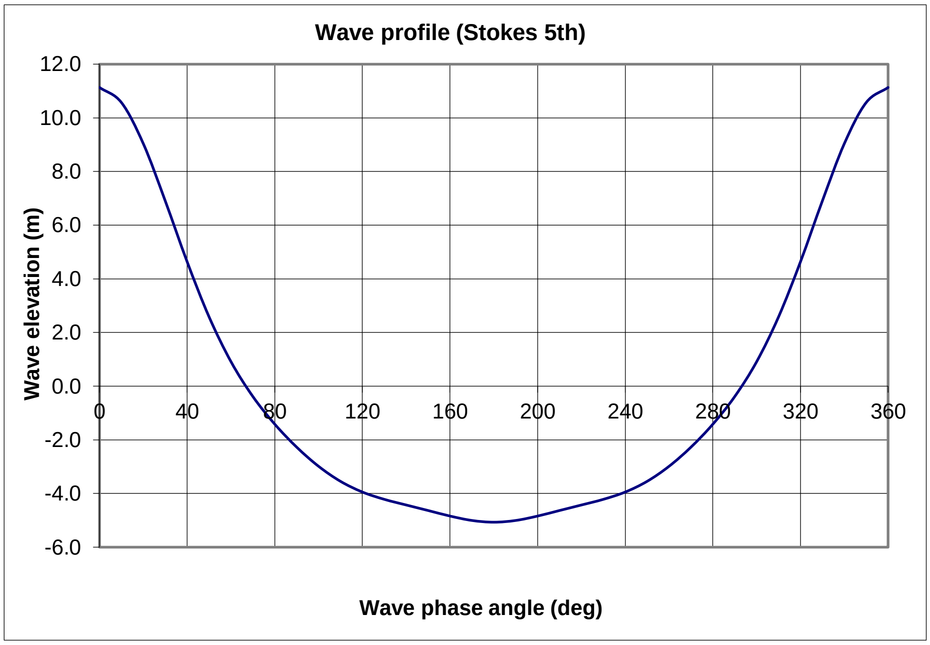
210.00	-2.3521	-0.4256
220.00	-2.1883	-0.5842
230.00	-1.9708	-0.7567
240.00	-1.6948	-0.9440
250.00	-1.3559	-1.1435
260.00	-0.9511	-1.3472
270.00	-0.4813	-1.5408
280.00	0.0471	-1.7039
290.00	0.6203	-1.8123
300.00	1.2166	-1.8421
310.00	1.8070	-1.7738
320.00	2.3577	-1.5969
330.00	2.8333	-1.3125
340.00	3.2006	-0.9339
350.00	3.4327	-0.4854
360.00	3.5121	0.0000

U_{wm} = max. wave particle velocity = 3.51 m/s

Wave profile h(t)

$$\eta(t)=\frac{L}{2\cdot\pi}\left\{\lambda\cdot\cos(\varphi)+\left(\lambda^2\cdot B_{22}+\lambda^4\cdot B_{24}\right)\cdot\cos(2\varphi)+\left(\lambda^3\cdot B_{33}+\lambda^5\cdot B_{35}\right)\cdot\cos(3\varphi)+\lambda^4\cdot B_{44}\cdot\cos(4\varphi)+\lambda^5\cdot B_{55}\cdot\cos(5\varphi)\right\}$$

ϕ (deg.)	η(t) (m)
0.00	11.1316
10.00	10.5703
20.00	9.0349
30.00	6.9058
40.00	4.6362
50.00	2.5835
60.00	0.9140
70.00	-0.3851
80.00	-1.4164
90.00	-2.2724
100.00	-2.9861
110.00	-3.5460
120.00	-3.9455
130.00	-4.2178
140.00	-4.4284
150.00	-4.6334
160.00	-4.8401
170.00	-5.0049
180.00	-5.0688
190.00	-5.0049
200.00	-4.8401
210.00	-4.6334
220.00	-4.4284
230.00	-4.2178
240.00	-3.9455
250.00	-3.5460
260.00	-2.9861
270.00	-2.2724
280.00	-1.4164
290.00	-0.3851
300.00	0.9140
310.00	2.5835
320.00	4.6362
330.00	6.9058
340.00	9.0349
350.00	10.5703
360.00	11.1316



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General data

(adjusted) Drag coefficient, C_D	0.7	-
(adjusted) Lift coefficient, C_L	0.9	-
(adjusted) Inertia coefficient, C_I	3.29	-
Sea water density, ρ_{sw}	1025	kg/m^3
Total OD pipeline, OD_tot	278.7	mm
Angle of attack relative to pipeline axis, wave	90	deg

ϕ [deg]	u_{w_perp} [m/s]	u_{cm_perp} [m/s]	u_{tot_perp} [m/s]	Fd [N/m]	Fl [N/m]
0.00	3.51	0.31	3.83	1462.9	1880.8
10.00	3.43	0.31	3.75	1402.8	1803.6
20.00	3.20	0.31	3.51	1234.3	1587.0
30.00	2.83	0.31	3.15	989.7	1272.5
40.00	2.36	0.31	2.67	713.1	916.9
50.00	1.81	0.31	2.12	449.3	577.7
60.00	1.22	0.31	1.53	233.9	300.7
70.00	0.62	0.31	0.93	87.1	112.0
80.00	0.05	0.31	0.36	13.0	16.7
90.00	-0.48	0.31	-0.17	-2.8	3.6
100.00	-0.95	0.31	-0.64	-40.7	52.4
110.00	-1.36	0.31	-1.04	-108.8	139.8
120.00	-1.69	0.31	-1.38	-190.9	245.5
130.00	-1.97	0.31	-1.66	-274.8	353.3
140.00	-2.19	0.31	-1.88	-351.6	452.1
150.00	-2.35	0.31	-2.04	-415.7	534.5
160.00	-2.47	0.31	-2.15	-463.5	596.0
170.00	-2.53	0.31	-2.22	-493.0	633.8
180.00	-2.56	0.31	-2.24	-502.9	646.6
190.00	-2.53	0.31	-2.22	-493.0	633.8
200.00	-2.47	0.31	-2.15	-463.5	596.0
210.00	-2.35	0.31	-2.04	-415.7	534.5
220.00	-2.19	0.31	-1.88	-351.6	452.1
230.00	-1.97	0.31	-1.66	-274.8	353.3
240.00	-1.69	0.31	-1.38	-190.9	245.5
250.00	-1.36	0.31	-1.04	-108.8	139.8
260.00	-0.95	0.31	-0.64	-40.7	52.4
270.00	-0.48	0.31	-0.17	-2.8	3.6
280.00	0.05	0.31	0.36	13.0	16.7
290.00	0.62	0.31	0.93	87.1	112.0
300.00	1.22	0.31	1.53	233.9	300.7
310.00	1.81	0.31	2.12	449.3	577.7
320.00	2.36	0.31	2.67	713.1	916.9
330.00	2.83	0.31	3.15	989.7	1272.5
340.00	3.20	0.31	3.51	1234.3	1587.0
350.00	3.43	0.31	3.75	1402.8	1803.6
360.00	3.51	0.31	3.83	1462.9	1880.8

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ϕ	a_{w_h}	$a_{w\_h\_perp}$	Fi	Fd+Fi	ABS(Fd+Fi)
[deg]	[m/s^2]	[m/s^2]	[N/m]	[N/m]	[N/m]
0.00	0.00	0.00	0.0	1462.9	1462.9
10.00	0.49	0.49	99.9	1502.6	1502.6
20.00	0.93	0.93	192.1	1426.4	1426.4
30.00	1.31	1.31	270.0	1259.7	1259.7
40.00	1.60	1.60	328.5	1041.7	1041.7
50.00	1.77	1.77	364.9	814.3	814.3
60.00	1.84	1.84	379.0	612.9	612.9
70.00	1.81	1.81	372.8	459.9	459.9
80.00	1.70	1.70	350.5	363.5	363.5
90.00	1.54	1.54	317.0	314.1	314.1
100.00	1.35	1.35	277.2	236.4	236.4
110.00	1.14	1.14	235.2	126.5	126.5
120.00	0.94	0.94	194.2	3.3	3.3
130.00	0.76	0.76	155.7	-119.1	119.1
140.00	0.58	0.58	120.2	-231.5	231.5
150.00	0.43	0.43	87.6	-328.2	328.2
160.00	0.28	0.28	57.1	-406.4	406.4
170.00	0.14	0.14	28.2	-464.8	464.8
180.00	0.00	0.00	0.0	-502.9	502.9
190.00	-0.14	-0.14	-28.2	-521.2	521.2
200.00	-0.28	-0.28	-57.1	-520.7	520.7
210.00	-0.43	-0.43	-87.6	-503.3	503.3
220.00	-0.58	-0.58	-120.2	-471.8	471.8
230.00	-0.76	-0.76	-155.7	-430.5	430.5
240.00	-0.94	-0.94	-194.2	-385.1	385.1
250.00	-1.14	-1.14	-235.2	-344.0	344.0
260.00	-1.35	-1.35	-277.2	-317.9	317.9
270.00	-1.54	-1.54	-317.0	-319.8	319.8
280.00	-1.70	-1.70	-350.5	-337.6	337.6
290.00	-1.81	-1.81	-372.8	-285.7	285.7
300.00	-1.84	-1.84	-379.0	-145.1	145.1
310.00	-1.77	-1.77	-364.9	84.4	84.4
320.00	-1.60	-1.60	-328.5	384.6	384.6
330.00	-1.31	-1.31	-270.0	719.7	719.7
340.00	-0.93	-0.93	-192.1	1042.2	1042.2
350.00	-0.49	-0.49	-99.9	1302.9	1302.9
360.00	0.00	0.00	0.0	1462.9	1462.9

Maximum absolute hydrodynamic force 1502.6 N/m

APPENDIX B On-Bottom Stability Calculations

(12 pages)

CLIENT	Wintershall Noordzee
PROJECT	D12-B Pipeline detailed design
SUBJECT	On-bottom stability calculation
DOCUMENT	18004-60-CAL-01502-01-01 - on bottom stability 10x12.7 flooded - omni waves.xlsm
FILE	D12B-67031002-PL-LA0580-GLOBAL-003
PREPARED BY	Pascal Ferier
REVIEW	Rev. 01
DATE	02/07/2018

1 OBJECTIVE:

Determine the pipeline/cable on-bottom stability check for the following conditions;

- Installation (condition 1)
- Soil liquefaction (condition 2)
- Uncovered pipeline during operation - no floating pipeline (condition 3)

2 CONTENTS.

CLIENT	Wintershall Noordzee
PROJECT	D12-B Pipeline detailed design
SUBJECT	On-bottom stability calculation
DOCUMENT	18004-60-CAL-01502-01-01 - on bottom stability 10x12.7 flooded - omni waves.xlsm
FILE	D12B-67031002-PL-LA0580-GLOBAL-003
PREPARED BY	Pascal Ferier
REVIEW	Rev. 01
DATE	02/07/2018

3 INPUT DATA AND ENVIRONMENTAL DATA

Nominal	W_t Wall thickness	Push the buttom to solve
[inch]	[mm]	
10	12.7	
0	14	
0	16	

Note: if you know the Wall-Thickness enter the value in the green cell and push the(wt) buttom to solve

Mechanical Design

INPUT DATA VALUES:

ENTER THREE DIFFERENTS LINES OR ONE MAIN LINE AND ONE PIGGYBACK LINE

	OD	W_t	ID	f_{tol}	CA	ρ_p	ρ_{SW}	ρ_{Soil}	ρ_{cont}	Internal Lining t_l	Internal Lining ρ_l	Coating t_c	Coating ρ_c	Concrete Coating t_{con}	Concrete Coating ρ_{con}	
Nominal	External Diameter	Wall thickness	Internal Diameter	Fabrication Tolerance	Corrosion Allowance	Density (pipe)	Density (Sea water)	Density (Liquified soil)	Density (contents)	Thickness	Density	Thickness	Density	Thickness	Density	Remarks:
[inch]	[mm]	[mm]	[mm]	%	[mm]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[mm]	[kg/m^3]	[mm]	[kg/m^3]	[mm]	[kg/m^3]	
10	273.1	12.70	247.7	0	0	7850	1025	1300	1025	0	0	2.8	900	0	0	

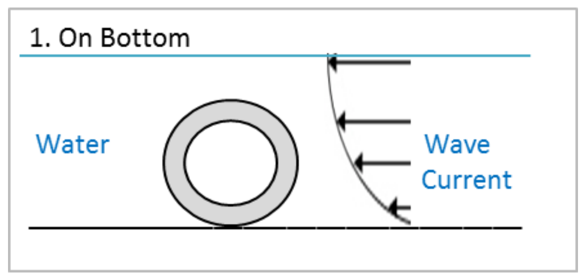
ENVIRONMENTAL DATA

WD	ss	SWL	D_{czr}	U_{czr}	α_c	H_s	T_z	α_c
Water Depth	Storm Surge	Storm Surge Water Level	Depth at with velocity is know	Current Velocity at reference hight	Angle of current attack	Wave Height	Wave Period	Angle of current attack
[m]	[m]	[m]	[m]	[m/s]	deg	[m]	[s]	[deg]
28.6	-0.85	27.75	-28.3	0.62	90	6.5	8.3	90

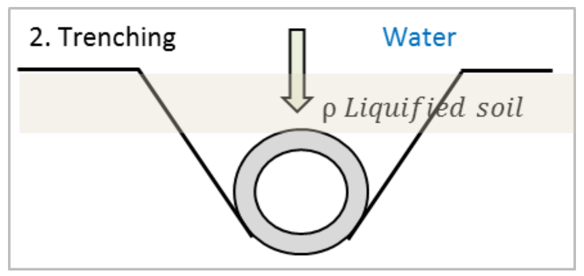
INPUT DATA VALUES: GO TO STOKES 5th TO SOLVE THE BIQUADRATIC EQ.

4 CONDITIONS TO EVALUATE

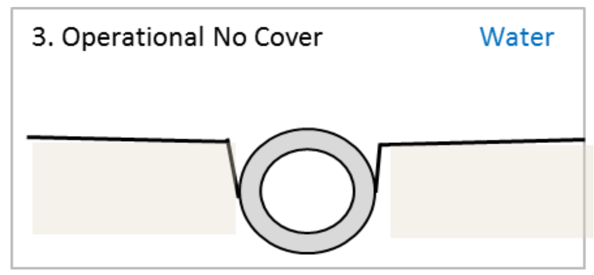
Condition 1:
On bottom stability. Installation, water filled, environmental loads (1 year condition).



Condition 2:
Trenching check, sinking through liquefied soil.
no environmental loads



Condition 3:
Operational no cover. Pipeline is operational (gas filled).
No environmental loads
No floating of pipeline



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5 THREE LINES RESULTS

Submerged weights and stability weight requirements

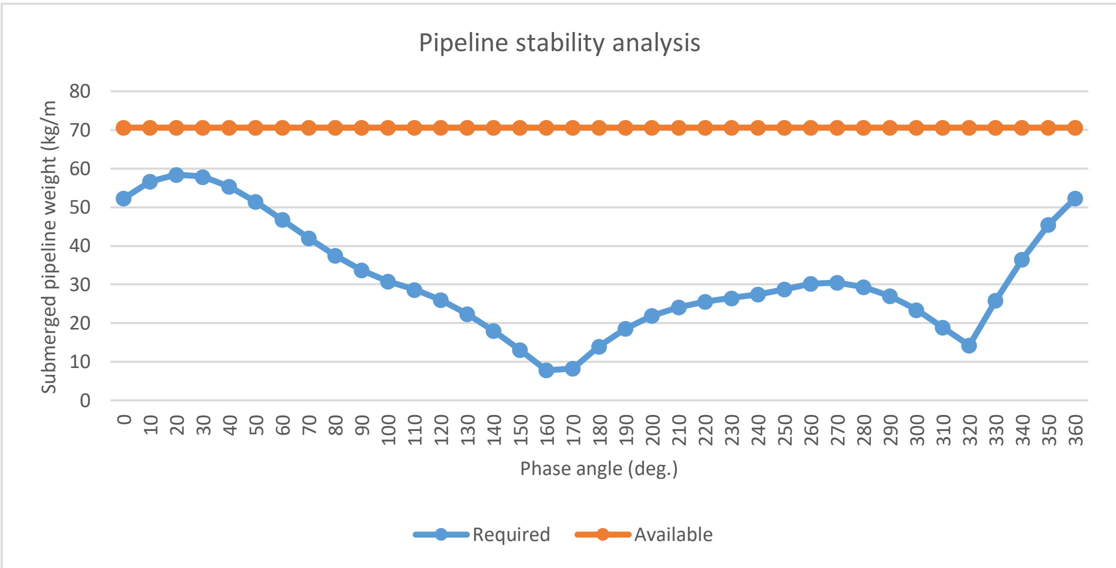
Pipeline Diameter	Submerged Weight	Condition 1: On bottom stability. Installation, water filled, (Kg/m)	Condition 2: Trenching check, sinking through liquefied soil. (Kg/m)	Condition 3: Operational no cover. Pipeline is operational (gas filled). (Kg/m)	Remarks
10	Available	70.6	182.5	83.7	
	Required	58.4	91.2	71.9	
	Additional Submerged	**Zero**	**Zero**	**ZERO**	
0	Available	0.0	0.0	0.0	
	Required	0.0	0.0	0.0	
	Additional Submerged	**0.0**	**0.0**	**0.0**	
0	Available	0.0	0.0	0.0	
	Required	0.0	0.0	0.0	
	Additional Submerged	**0.0**	**0.0**	**0.0**	

CONDITION 1: RESULTS

10

0

0



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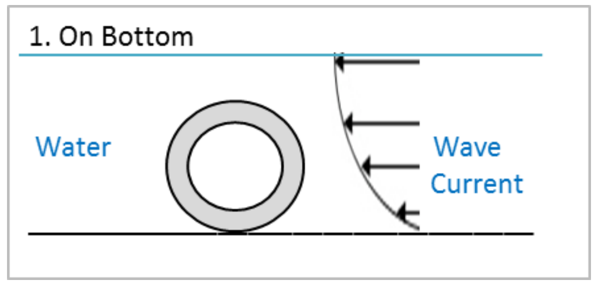
a BOUYANCY FORCE

PIPE DATA

Nominal	OD External Diameter	W_t Wall thickness	ID Internal Diameter	t_{min} Minimum wall thickness	ID Internal diameter	A_S Cross sectional area	SEC Section modulus	I_S Moment of inertia	W_{pi} Pipe weight	W_I Lining weight	W_c Coating weight	W_{con} Concrete weight
[inch]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm^2]	[mm^3]	[mm^4]	[Kg/m]	[Kg/m]	[Kg/m]	[Kg/m]
10	273.1	12.7	247.7	12.7	247.7	10,390	6.5E+05	8.8E+07	81.6	0	2.2	0.0
0	0	0	0	0	0	0	#DIV/0!	0.0E+00	0.0	0	0.0	0.0
0	0	0	0	0	0	0	#DIV/0!	0.0E+00	0.0	0	0.0	0.0
				(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)



EQUATIONS USED

(1) $t_{min} = W_t * (1 - f_{tol}) - CA$

(2) $ID = OD - 2 * t_{min}$

(3) $A_S = \frac{\pi}{4} * (OD^2 - ID^2)$

(4) $SEC = \pi * \frac{(OD^4 - ID^4)}{32 * OD}$

(5) $I_S = \frac{\pi}{64} * (OD^4 - ID^4)$

(6) $W_{pi} = A_S * \rho_P$

(7) $W_I = \frac{\pi}{4} * \left[\frac{ID^2 - (ID - 2 * t_I)^2}{10^6}\right] * \rho_I$

(8) $W_c = \frac{\pi}{4} * \left[\frac{(OD + 2 * t_c)^2 - (OD)^2}{10^6}\right] * \rho_c$

(9) $W_{con} = \frac{\pi}{4} * \left[\frac{(OD + 2 * t_c + 2 * t_{con})^2 - (OD + 2 * t_c)^2}{10^6}\right] * \rho_{con}$

Buoyancy force

Nominal	OD External Diameter	OD_{TOTAL} External Diameter	F_B Buoyancy force	W_{cont} Contents weight	W_r Pipeline weight in air	W_{sm} Submerged pipeline weight
[inch]	[mm]	[mm]	[Kg/m]	[Kg/m]	[Kg/m]	[Kg/m]
10	273.1	278.7	-62.5	49.4	133.1	70.6
0	0	0	0.0	0.0	0.0	0.0
0	0	0	0.0	0.0	0.0	0.0
		(10)	(11)	(12)	(13)	(14)

(10) $OD_{TOTAL} = OD + 2 * t_c + 2 * t_{con}$

(11) $F_B = \frac{\pi}{4} * (OD_{TOTAL})^2 * \rho_W$

(12) $W_{cont} = \frac{\pi}{4} * \left[\frac{(ID - 2 * t_I)^2}{10^6}\right] * \rho_{cont}$

(13) $W_r = W_{pi} + W_I + W_c + W_{con} + W_{cont}$

(14) $W_{sm} = W_r - F_B$

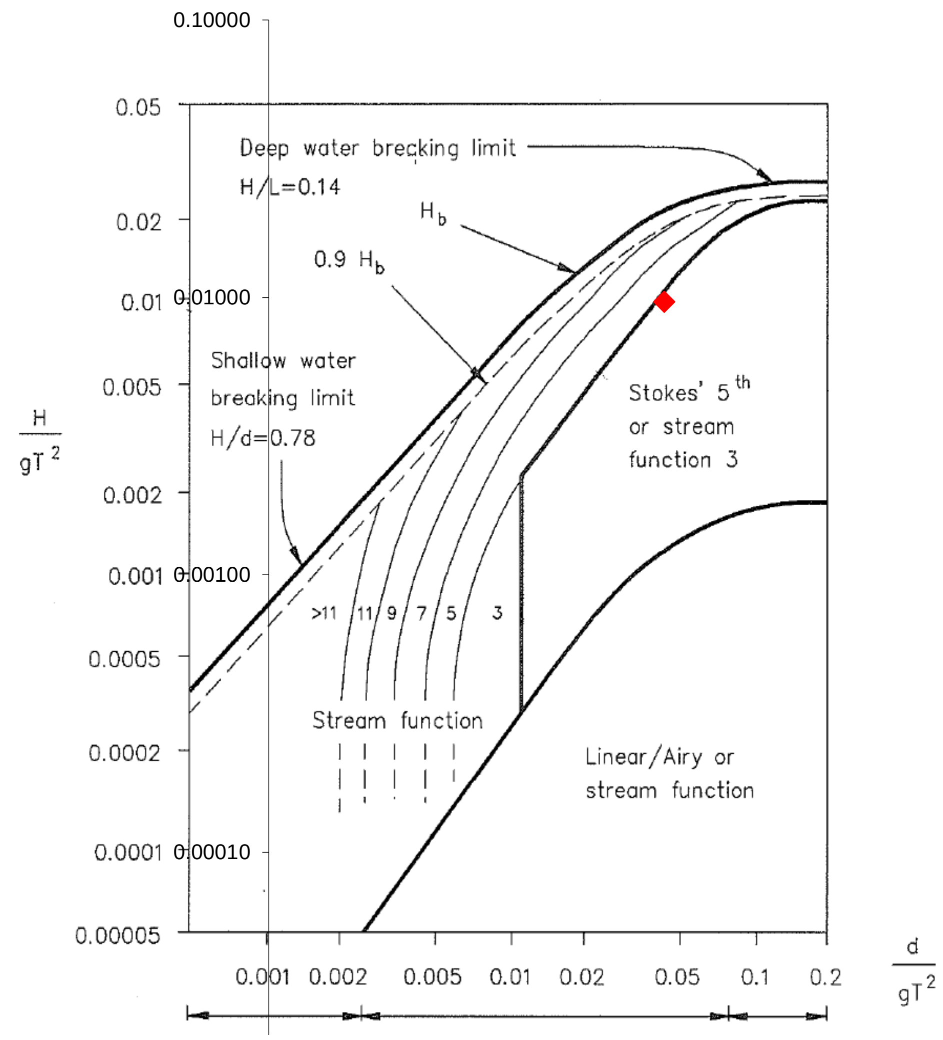
b WAVE THEORY APPLICABILITY

According with the literature to evaluate the applicability of the wave theory, It is used the next figure. Wave theory applicability for test matrix (King 2011, p52).

To select the theory to apply. The following factors are calculated:

(15) $\frac{H_S}{g * T_Z} =$ 0.009628

(16) $\frac{SWL}{g * T_Z} =$ 0.04110368



In this case the theory to apply is Fifth Order Stokes Theory for Steady Waves

Where: (g) is the gravity 9.81 m/s^2

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enersea®

c STOKES 5th WAVE ANALYSIS

WD	SS	SWL	D_{czr}	U_{czr}	α_c	H_s	T_z	α_c	L_O	L
Water Depth	Storm Surge	Storm Surge Water Level	Depth at with velocity is know	Current Velocity at reference hight	Angle of current attack	Wave Height	Wave Period	Angle of current attack	Deep water wave length	Estimate actual wave length
[m]	[m]	[m]	[m]	[m/s]	deg	[m]	[s]	[deg]	[m]	[m]
28.6	-0.85	27.75	-28.3	0.62	90	6.5	8.3	90	107.6	104.7
									(16)	

Press here to solve. Start with L = Lo

(16) $$L_O = \frac{g * T_Z^2}{2 * \pi}$$

(17) $$\frac{\pi * H_S}{SWL} - \frac{L}{SWL} * [\lambda + \lambda^3 + B_{33} + \lambda^5 * (B_{35} + B_{55})] = 0$$

(18) $$\frac{SWL}{L_O} - \frac{SWL}{L} * tanh\left(\frac{2 * \pi * SWL}{L}\right) * [\lambda^4 * C_2 + \lambda^2 * C_1 + 1] = 0$$

Choosing L and solving for λ in (18) results in 4 roots for (17)

A	B	λ (1)	λ (2)	λ (3)	λ (4)	Eq (17)	Eq (18)
0.2580	0.2468	0.1905	#NUM!	-0.1905	#NUM!	-0.0002	0.00000
						(17)	(18)

The root λ (1) solved the equations (17) and (18)

(19) $$A = \frac{SWL}{L_O}$$

(20) $$B = \frac{SWL}{L} * tanh\left(\frac{2 * \pi * SWL}{L}\right)$$

To solve equations biquadratic in (18)

a	b	c
0.498414	0.291305	-0.0112

(21) $$\lambda = \pm\sqrt{y}$$

(22) $$y = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

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a COEFFICIENTS

S	C	A_{11}	A_{13}	A_{15}	A_{22}	A_{24}	A_{33}	A_{35}	A_{44}	A_{55}	B_{22}	B_{24}	B_{33}	B_{35}	B_{44}	B_{55}	C_1	C_2	C_3	C_4
2.5497	2.7388	0.3922	-0.3350	-0.5027	0.0089	0.0465	-0.0004	0.0048	-2.94E-06	0.0000	0.6610	1.0023	0.5762	2.0211	0.5935	0.6826	1.1804	2.0197	0.0358	0.0188

(23) $$s = \sinh\left(\frac{2*\pi*SWL}{L}\right)$$

(24) $$C = \cosh\left(\frac{2*\pi*SWL}{L}\right)$$

(25) $$A_{11} = \frac{1}{S}$$

(26) $$A_{13} = \frac{-C^2*(5*C^2+1)}{8*S^5}$$

(27) $$A_{15} = -\frac{1184*C^{10}-1440*C^8-1992*C^6+2641*C^4-249*C^2+18}{1536*S^{11}}$$

(28) $$A_{22} = \frac{3}{8*S^4}$$

(29) $$A_{24} = \frac{192*C^8-424*C^6-312*C^4+480*C^2-17}{768*S^{10}}$$

(30) $$A_{33} = \frac{13-4*C^2}{64*S^7}$$

(31) $$A_{35} = \frac{512*C^{12}+4224*C^{10}-6800*C^8-12808*C^6+16704*C^4-3154*C^2-107}{4096*S^{13}*(6*C^2-1)}$$

(32) $$A_{44} = \frac{80*C^6-816*C^4+1338*C^2-197}{1536*S^{10}*(6*C^2-1)}$$

(33) $$A_{55} = -\frac{2880*C^{10}-72480*C^8+324000*C^6-432000*C^4+163470*C^2-16245}{61440*S^{11}*(6*C^2-1)*(8*C^4-11*C^2+3)}$$

(34) $$B_{22} = \frac{(2*C^2+1)*C}{4*S^3}$$

(35) $$B_{24} = \frac{(272*C^8-504*C^6-192*C^4+322*C^2+21)*C}{384*S^9}$$

(36) $$B_{33} = \frac{(8*C^6+1)*3}{64*S^6}$$

(37) $$B_{35} = \frac{88128*C^{14}-208224*C^{12}+70848*C^{10}+54000*C^8-21816*C^6+6264*C^4-54*C^2-81}{12288*S^{12}*(6*C^2-1)}$$

(38) $$B_{44} = C*\frac{768*C^{10}-488*C^8-48*C^6+48*C^4+106*C^2-21}{384*S^9*(6*C^2-1)}$$

(39) $$B_{55} = \frac{192000*C^{16}-26720*C^{14}+83680*C^{12}+20160*C^{10}-7280*C^8+7160*C^6-1800*C^4-1050*C^2+225}{12288*S^{10}*(6*C^2-1)*(8*C^4-11*C^2+3)}$$

(40) $$C_1 = \frac{8*C^4-8*C^2+9}{8*S^4}$$

(41) $$C_2 = \frac{3840*C^{12}-4096*C^{10}+2592*C^8-1008*C^6+5944*C^4-1830*C^2+147}{512*S^{10}(6*C^2-1)}$$

(42) $$C_3 = \frac{1}{4*C*S}$$

(43) $$C_4 = \frac{12*C^8+36*C^6-162*C^4+141*C^2-27}{192*S^9*C}$$

WITH THE COEFFIENTS AND λ CALCULATE k₁, K₂, K₃ AND K₄

K_1	K_2	K_3	K_4	K_5
0.0723	0.0004	0.0000	0.0000	0.0000

(44) $$K_1 = \lambda*A_{11}+\lambda^3*A_{13}+\lambda^5*A_{15}$$

(45) $$K_2 = \lambda^2*A_{22}+\lambda^4*A_{24}$$

(46) $$K_3 = \lambda^3*A_{33}+\lambda^5*A_{35}$$

(47) $$K_4 = \lambda^4*A_{44}$$

(48) $$K_5 = \lambda^5*A_{55}$$

b Horizontal wave particle velocities

Nominal	OD_{TOTAL} External Diameter	Water depth at which data required (Z)
[inch]	[mm]	[m]
10	278.7	0.2787
0	0	0.0000
0	0	0.0000

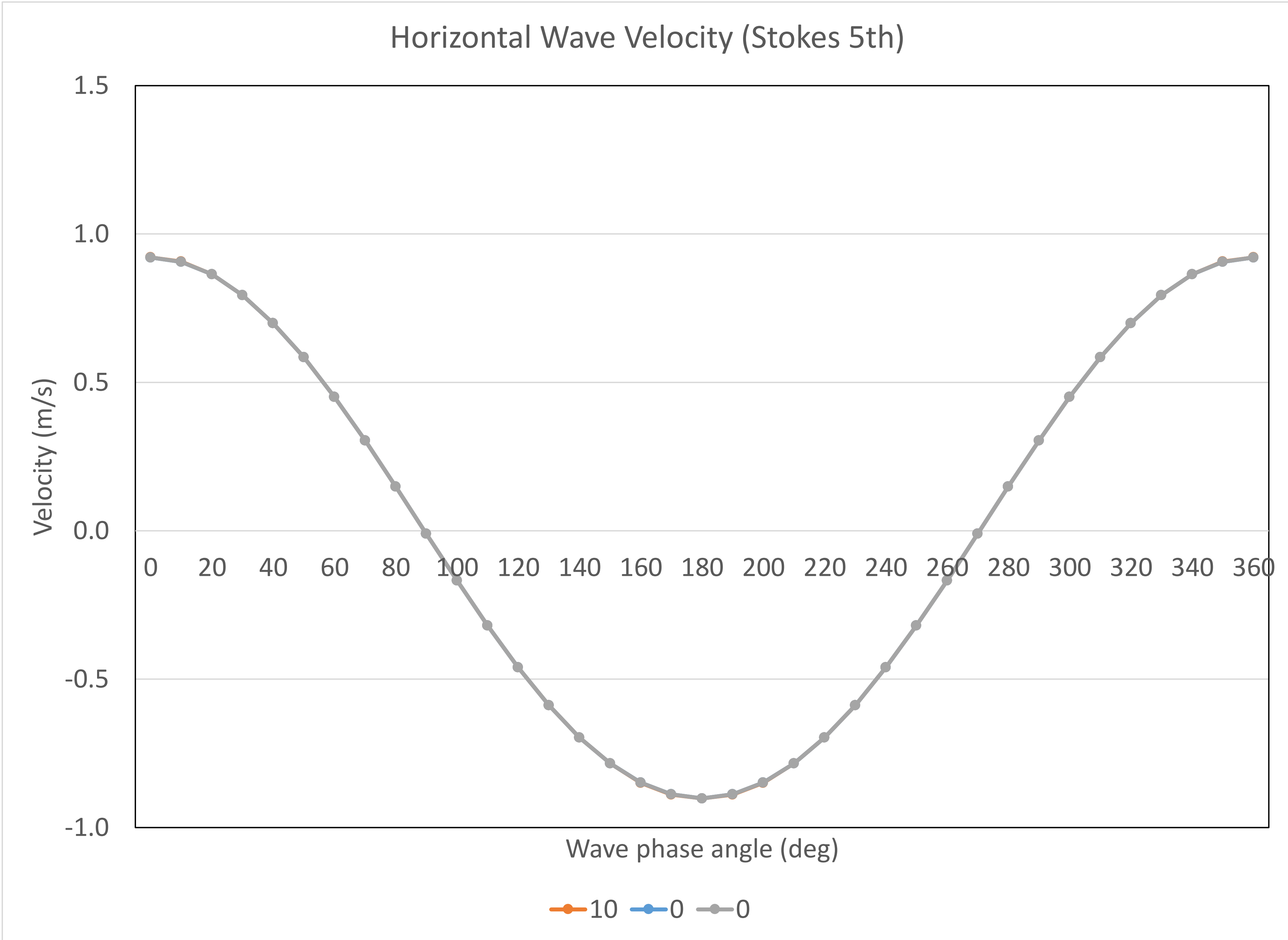
Horizontal velocity, U_w

$$U_w = \frac{L}{T_Z} * \sum_{n=1}^{5} n * K_n * \cosh\left(\frac{n*2*\pi*z}{L}\right) * \cos(n*\varphi) \quad (49)$$

Horizontal acceleration, $a_{w,h}$

$$a_{w,h} = \frac{2*\pi*L}{T_Z^2} * \sum_{n=1}^{5} n^2 * K_n * \cosh\left(\frac{n*2*\pi*z}{L}\right) * \sin(n*\varphi) \quad (50)$$

	10		0		0	
φ	U_w	$a_{w,h}$	U_w	$a_{w,h}$	Uw	aw,h
[deg.]	[m/s]	[m/s^2]	[m/s]	[m/s^2]	[m/s]	[m/s^2]
0	0.9211	0.0000	0.9210	0.0000	0.9210	0.0000
10	0.9067	0.1248	0.9066	0.1247	0.9066	0.1247
20	0.8639	0.2453	0.8638	0.2453	0.8638	0.2453
30	0.7942	0.3576	0.7941	0.3575	0.7941	0.3575
40	0.7000	0.4579	0.6999	0.4578	0.6999	0.4578
50	0.5843	0.5430	0.5842	0.5429	0.5842	0.5429
60	0.4510	0.6103	0.4509	0.6102	0.4509	0.6102
70	0.3044	0.6579	0.3044	0.6578	0.3044	0.6578
80	0.1492	0.6847	0.1492	0.6846	0.1492	0.6846
90	-0.0097	0.6902	-0.0097	0.6901	-0.0097	0.6901
100	-0.1674	0.6747	-0.1674	0.6746	-0.1674	0.6746
110	-0.3192	0.6391	-0.3192	0.6390	-0.3192	0.6390
120	-0.4607	0.5849	-0.4606	0.5848	-0.4606	0.5848
130	-0.5876	0.5141	-0.5876	0.5141	-0.5876	0.5141
140	-0.6966	0.4290	-0.6965	0.4290	-0.6965	0.4290
150	-0.7846	0.3322	-0.7845	0.3322	-0.7845	0.3322
160	-0.8491	0.2265	-0.8490	0.2265	-0.8490	0.2265
170	-0.8885	0.1148	-0.8884	0.1147	-0.8884	0.1147
180	-0.9018	0.0000	-0.9017	0.0000	-0.9017	0.0000
190	-0.8885	-0.1148	-0.8884	-0.1147	-0.8884	-0.1147
200	-0.8491	-0.2265	-0.8490	-0.2265	-0.8490	-0.2265
210	-0.7846	-0.3322	-0.7845	-0.3322	-0.7845	-0.3322
220	-0.6966	-0.4290	-0.6965	-0.4290	-0.6965	-0.4290
230	-0.5876	-0.5141	-0.5876	-0.5141	-0.5876	-0.5141
240	-0.4607	-0.5849	-0.4606	-0.5848	-0.4606	-0.5848
250	-0.3192	-0.6391	-0.3192	-0.6390	-0.3192	-0.6390



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260	-0.1674	-0.6747	-0.1674	-0.6746	-0.1674	-0.6746
270	-0.0097	-0.6902	-0.0097	-0.6901	-0.0097	-0.6901
280	0.1492	-0.6847	0.1492	-0.6846	0.1492	-0.6846
290	0.3044	-0.6579	0.3044	-0.6578	0.3044	-0.6578
300	0.4510	-0.6103	0.4509	-0.6102	0.4509	-0.6102
310	0.5843	-0.5430	0.5842	-0.5429	0.5842	-0.5429
320	0.7000	-0.4579	0.6999	-0.4578	0.6999	-0.4578
330	0.7942	-0.3576	0.7941	-0.3575	0.7941	-0.3575
340	0.8639	-0.2453	0.8638	-0.2453	0.8638	-0.2453
350	0.9067	-0.1248	0.9066	-0.1247	0.9066	-0.1247
360	0.9211	0.0000	0.9210	0.0000	0.9210	0.0000

Max Wave Particle Velocity U_{wm} = **0.921141 m/s**

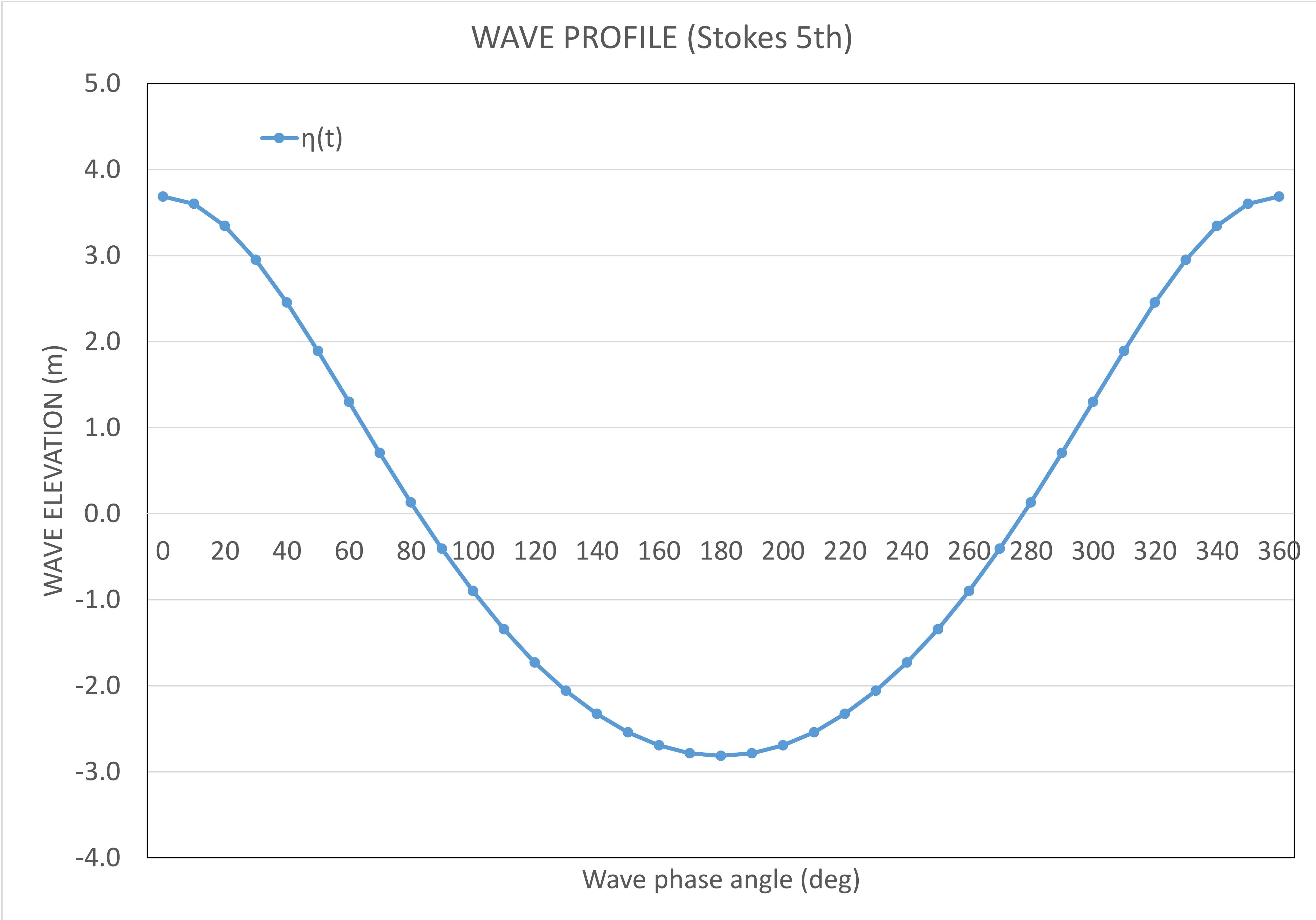
c WAVE PROFILE η(t)

φ	η(t)
[deg.]	**[m]**
0	3.6855
10	3.5978
20	3.3440
30	2.9500
40	2.4519
50	1.8887
60	1.2961
70	0.7028
80	0.1297
90	-0.4085
100	-0.9020
110	-1.3440
120	-1.7306
130	-2.0595
140	-2.3299
150	-2.5415
160	-2.6938
170	-2.7857
180	-2.8165

φ	η(t)
[deg.]	**[m]**
190	-2.7857
200	-2.6938
210	-2.5415
220	-2.3299
230	-2.0595
240	-1.7306
250	-1.3440
260	-0.9020
270	-0.4085
280	0.1297
290	0.7028
300	1.2961
310	1.8887
320	2.4519
330	2.9500
340	3.3440
350	3.5978
360	3.6855

c WAVE PROFILE η(t)

(51) $$\eta(t)=\frac{L}{2\cdot\pi}\left\{\lambda\cdot\cos(\varphi)+\left(\lambda^2\cdot B_{22}+\lambda^4\cdot B_{24}\right)\cdot\cos(2\varphi)+\left(\lambda^3\cdot B_{33}+\lambda^5\cdot B_{35}\right)\cdot\cos(3\varphi)+\lambda^4\cdot B_{44}\cdot\cos(4\varphi)+\lambda^5\cdot B_{55}\cdot\cos(5\varphi)\right\}$$



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Condition 1: **On bottom stability. Installation, water filled,**

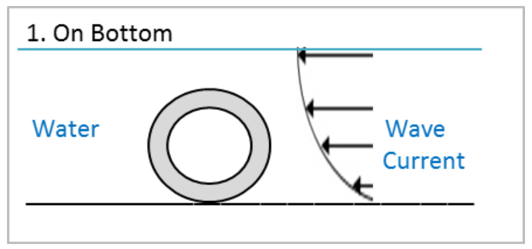
Nominal	ODTOTAL External Diameter	Wave Lenght	Maximum orbital particle velocity	Keulegan-Carpenter number	Pipeline embedment (ε)	Pipeline embedment (ε)	Drag coefficient	Lift coefficient	Inertia coefficient	Soil Submerged density	Angle of internal friction (ϕ)	Potyondy coefficient (pot)	Friction factor pipe/soil (f)	Passive soil resistance coefficient (Kp)	Passive soil resistance (Fp)	Available submerged weight	Required submerged weight	Additional Weight Required	CHECK
[inch]	[mm]	[m]	[m/s]		%	[mm]				[Kg/m^3]	[deg]				[Kg/m]	[Kg/m]	[Kg/m]	[Kg/m]	
10	278.7	104.69	0.92	27.43	0	0	0.70	0.90	3.29	1000	34	0.80	0.51	3.54	0.00	70.61	58.4	Zero	OK
				(52)									(53)	(54)	(55)	(14)	(60)		

(52) $$KC = \frac{U_{wm} * T_Z}{OD_{TOTAL}}$$

(53) $$f = \tan(pot * \varphi)$$

(54) $$K_p = \frac{1 + \tan(\varphi)}{1 - \tan(\varphi)}$$

(55) $$F_p = \left(\frac{1}{2}\right) * \rho_{soil} * \varepsilon^2 * K_p$$



The required minimum submerged pipeline weight

Nominal	ODTOTAL External Diameter	Horizontal current particle velocity (from current sheet) (Ucm)	Safety factor (SF)	Max. required submerged weight
[inch]	[mm]	[m/s]		[Kg/m]
10	278.7	0.28	1.1	58.4
		(56)		

(56) $$U_{cm} = 0{,}875 * U_{czr} * \left(\frac{OD_{total}}{D_{czr}}\right)^{\frac{1}{7}} * \sin(\alpha c)$$

(57) $$F_d = 0{,}5 * \rho_{sw} * C_d * (U_w + U_{cm})^2 * OD_{total}$$

(58) $$F_L = 0{,}5 * \rho_{sw} * C_L * (U_w + U_{cm})^2 * OD_{total}$$

(59) $$F_i = 0{,}25 * \pi * \rho_{sw} * C_M * (OD_{total})^2 * a_{w,h}$$

(60) $$W_{req} = SF * F_L + \frac{SF * (F_d + F_i) - F_p}{f}$$

Coefficients and Interpolation tables

% Embedment	C_D	C_L	C_I
0	0.70	0.90	3.29
10	0.63	0.90	2.80
20	0.53	0.81	2.30
30	0.44	0.77	1.89
40	0.35	0.72	1.48

		% Embedment	C_D	C_L	C_I
10	Lim Inf	0	0.70	0.90	3.29
	Lim Sup	10	0.63	0.90	2.80
	Valor	0	0.70	0.90	3.29
0	Lim Inf	0	0.70	0.90	3.29
	Lim Sup	10	0.63	0.90	2.80
	Valor	0	0.70	0.90	3.29
0	Lim Inf	0	0.70	0.90	3.29
	Lim Sup	10	0.63	0.90	2.80
	Valor	0	0.70	0.90	3.29

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PREPARED BY	Pascal Ferier
REVIEW	Rev. 01
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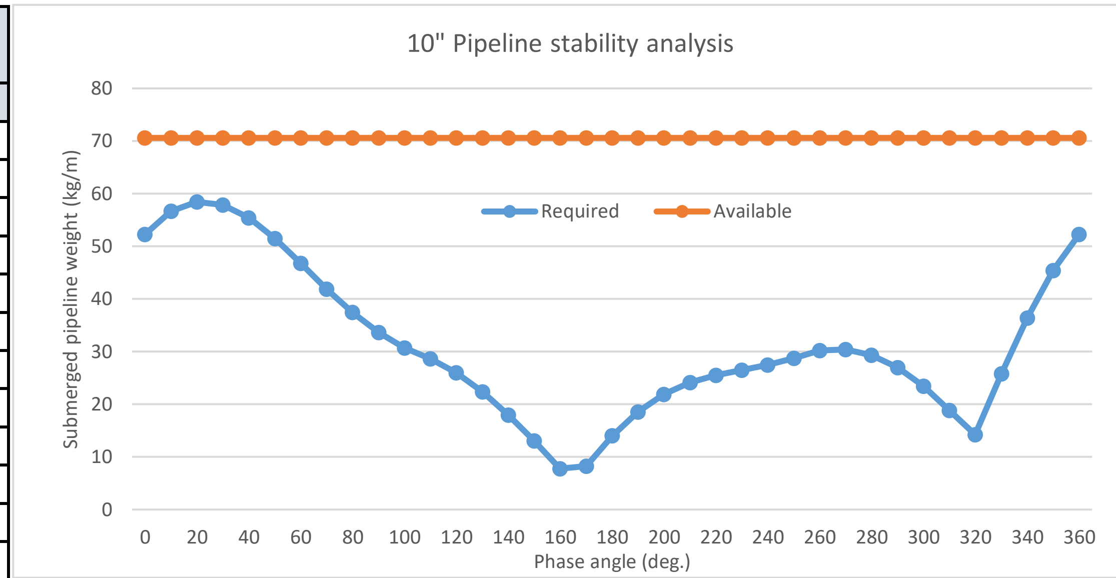
10	**PIPE**	(56)		(57)	(58)			(59)	(55)	(60)		(14)
φ	**Uw**	**Ucm**	**Utotal**	**Fd**	**FL**	**aw,h**	**aw,h (90deg)**	**Fi**	**Fp**	**Wreq**	**Wreq**	**Wa**
[deg.]	**[m/s]**	**[m/s]**	**[m/s]**	**[N/m]**	**[N/m]**	**[m/s^2]**	**[m/s^2]**	**[N/m]**	**[N/m]**	**[N/m]**	**[Kg/m]**	**[Kg/m]**
0	0.9211	0.2803	1.2015	144.3	185.6	0.0000	0.0000	0.0	0.00	513.0	52.3	70.6
10	0.9067	0.2803	1.1871	140.9	181.1	0.1248	0.1248	25.7	0.00	555.7	56.7	70.6
20	0.8639	0.2803	1.1443	130.9	168.3	0.2453	0.2453	50.5	0.00	573.4	58.4	70.6
30	0.7942	0.2803	1.0746	115.5	148.4	0.3576	0.3576	73.6	0.00	567.8	57.9	70.6
40	0.7000	0.2803	0.9803	96.1	123.5	0.4579	0.4579	94.2	0.00	543.2	55.4	70.6
50	0.5843	0.2803	0.8646	74.7	96.1	0.5430	0.5430	111.7	0.00	504.8	51.5	70.6
60	0.4510	0.2803	0.7313	53.5	68.8	0.6103	0.6103	125.5	0.00	458.8	46.8	70.6
70	0.3044	0.2803	0.5847	34.2	44.0	0.6579	0.6579	135.3	0.00	411.2	41.9	70.6
80	0.1492	0.2803	0.4296	18.4	23.7	0.6847	0.6847	140.9	0.00	367.1	37.4	70.6
90	-0.0097	0.2803	0.2707	7.3	9.4	0.6902	0.6902	142.0	0.00	329.9	33.6	70.6
100	-0.1674	0.2803	0.1129	1.3	1.6	0.6747	0.6747	138.8	0.00	301.6	30.7	70.6
110	-0.3192	0.2803	-0.0389	-0.2	0.2	0.6391	0.6391	131.5	0.00	281.3	28.7	70.6
120	-0.4607	0.2803	-0.1803	-3.3	4.2	0.5849	0.5849	120.3	0.00	255.2	26.0	70.6
130	-0.5876	0.2803	-0.3073	-9.4	12.1	0.5141	0.5141	105.8	0.00	219.5	22.4	70.6
140	-0.6966	0.2803	-0.4163	-17.3	22.3	0.4290	0.4290	88.3	0.00	176.3	18.0	70.6
150	-0.7846	0.2803	-0.5042	-25.4	32.7	0.3322	0.3322	68.3	0.00	127.8	13.0	70.6
160	-0.8491	0.2803	-0.5688	-32.3	41.6	0.2265	0.2265	46.6	0.00	76.2	7.8	70.6
170	-0.8885	0.2803	-0.6082	-37.0	47.6	0.1148	0.1148	23.6	0.00	80.9	8.3	70.6
180	-0.9018	0.2803	-0.6215	-38.6	49.6	0.0000	0.0000	0.0	0.00	137.3	14.0	70.6
190	-0.8885	0.2803	-0.6082	-37.0	47.6	-0.1148	-0.1148	-23.6	0.00	182.0	18.6	70.6
200	-0.8491	0.2803	-0.5688	-32.3	41.6	-0.2265	-0.2265	-46.6	0.00	214.7	21.9	70.6
210	-0.7846	0.2803	-0.5042	-25.4	32.7	-0.3322	-0.3322	-68.3	0.00	236.6	24.1	70.6
220	-0.6966	0.2803	-0.4163	-17.3	22.3	-0.4290	-0.4290	-88.3	0.00	250.5	25.5	70.6
230	-0.5876	0.2803	-0.3073	-9.4	12.1	-0.5141	-0.5141	-105.8	0.00	259.9	26.5	70.6
240	-0.4607	0.2803	-0.1803	-3.3	4.2	-0.5849	-0.5849	-120.3	0.00	269.1	27.4	70.6
250	-0.3192	0.2803	-0.0389	-0.2	0.2	-0.6391	-0.6391	-131.5	0.00	281.9	28.7	70.6
260	-0.1674	0.2803	0.1129	1.3	1.6	-0.6747	-0.6747	-138.8	0.00	296.1	30.2	70.6
270	-0.0097	0.2803	0.2707	7.3	9.4	-0.6902	-0.6902	-142.0	0.00	298.6	30.4	70.6
280	0.1492	0.2803	0.4296	18.4	23.7	-0.6847	-0.6847	-140.9	0.00	288.1	29.4	70.6
290	0.3044	0.2803	0.5847	34.2	44.0	-0.6579	-0.6579	-135.3	0.00	264.9	27.0	70.6
300	0.4510	0.2803	0.7313	53.5	68.8	-0.6103	-0.6103	-125.5	0.00	229.9	23.4	70.6
310	0.5843	0.2803	0.8646	74.7	96.1	-0.5430	-0.5430	-111.7	0.00	184.8	18.8	70.6
320	0.7000	0.2803	0.9803	96.1	123.5	-0.4579	-0.4579	-94.2	0.00	139.9	14.3	70.6
330	0.7942	0.2803	1.0746	115.5	148.4	-0.3576	-0.3576	-73.6	0.00	252.9	25.8	70.6
340	0.8639	0.2803	1.1443	130.9	168.3	-0.2453	-0.2453	-50.5	0.00	357.3	36.4	70.6
350	0.9067	0.2803	1.1871	140.9	181.1	-0.1248	-0.1248	-25.7	0.00	445.9	45.4	70.6
360	0.9211	0.2803	1.2015	144.3	185.6	0.0000	0.0000	0.0	0.00	513.0	52.3	70.6
Maximum required submerged weight (Kg/m) =					**58.4**				Max	573.4	58.4	



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REVIEW	Rev. 01
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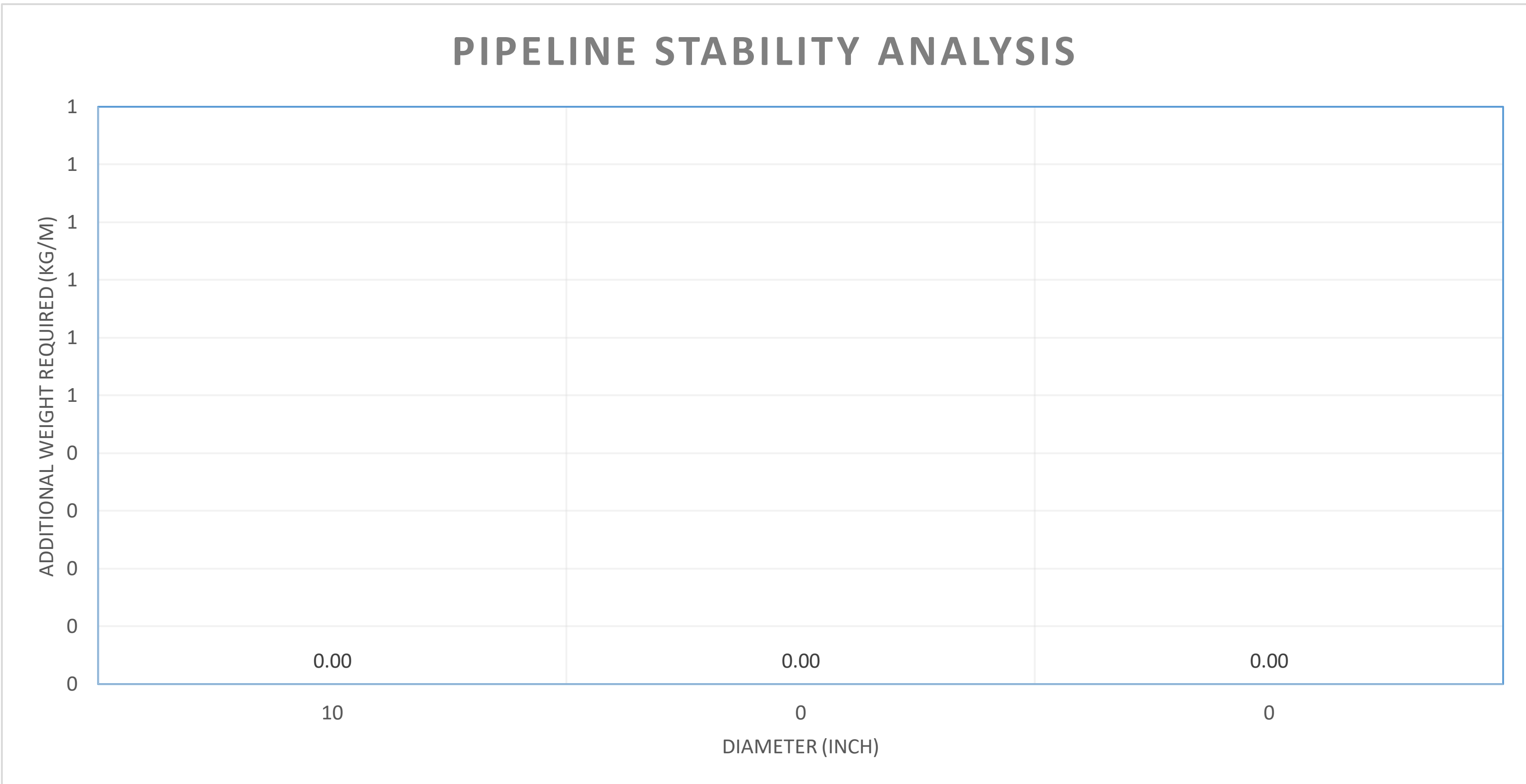
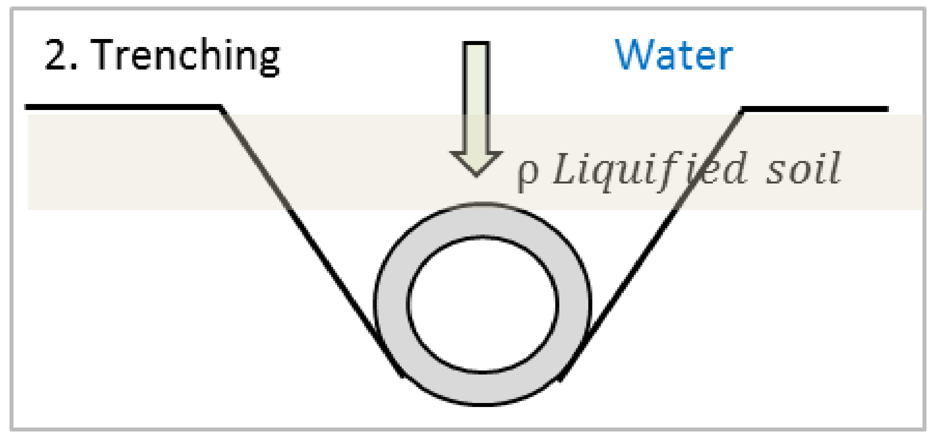
Condition 2: **Trenching check, sinking through liquefied soil.**

	ID	OD	OD_{TOTAL}	ρ_p	ρcont	ρsw	ρ_{Soil}	Coating		Concrete Coating											
Nominal	Internal Diameter	External Diameter	OD_{TOTAL} External Diameter	Density (pipe)	Density (contents)	Density (Sea water)	Density (Liquified soil)	t_c Thickness	ρ_c Density	t_{con} Thickness	ρ_{con} Density	Weight in air flooded	Submerged weight flooded	Weight content pipe	Weight in liquified soil flooded	Buoyancy Liquefied soil	Design factor	Contingency factor	Required pipeline weight	Additional Weight Required	CHECK
[inch]	[m]	[m]	[m]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[mm]	[kg/m^3]	[mm]	[kg/m^3]	[kg/m]	[kg/m]	[kg/m]	[kg/m]	[kg/m]			[Kg/m]	[Kg/m]	
10	0.248	0.273	0.279	7850	1025	1025	1300	2.8	900	0	0	133.14	70.61	49.39	103.22	79.31	1.15	1.00	91.20	Zero	OK
0	0.000	0.000	0.000	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	1.15	1.00	0.00	0.00	OK
0	0.000	0.000	0.000	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	1.15	1.00	0.00	0.00	OK





APPENDIX C Span Analysis Calculations

(15 pages)

Static & Dynamic Span - 10" x 12.7mm

Condition Overview

	Pressure (barg)	Temp. (deg. C)	Content (kg/m3)
Installation (P_{in}, T_{in})	2	15	1025
Hydrotest (P_t, T_t)	202	15	1025
Design (P_d, T_d)	148	65	90

Pipeline properties

Nominal diameter		OD_{nom} =	10"	
Nominal diameter		OD_{nom} =	273.1	mm
Nominal wall thickness		d_{nom} =	12.7	mm
Internal diameter	$ID = OD_{nom} - 2 \cdot d_{nom}$	ID =	247.7	mm
Cross sectional area of steel	$A_s = \frac{\pi}{4} \cdot \{OD_{nom}^2 - ID^2\}$	A_s =	10389	mm^2
Section modulus	$W_s = \frac{\pi}{32} \cdot \frac{\{OD_{nom}^4 - ID^4\}}{OD_{nom}}$	W_s =	646438	mm^3
Moment of Inertia	$I_s = \frac{\pi}{64} \cdot \{OD_{nom}^4 - ID^4\}$	I_s =	88271060	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	5.5	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	9.0	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	264.1	mm

Piggyback

Nominal diameter	$OD_{nom,p}$ =	0	mm
Nominal wall thickness	$d_{nom,p}$ =	0.0	mm

Coating data

Thickness line pipe	=	2.8	mm
Thickness piggyback	=	0	mm
Density	=	900	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Material

	=	L360NB	
Design temperature	T_d =	65	°C
Yield at ambient/hydrotest temperature	R_e =	360.00	N/mm^2
Yield at design temperature	R_{ed} =	343.20	N/mm^2
Density	ρ_{st} =	7850	kg/m3
Youngs modulus	E_s =	210000	N/mm^2
Poisson's ratio	u =	0.3	-
Linear thermal expansion coefficient	a =	1.16E-05	m/m/°C

Weights

		installation (N/m)	hydrotest (N/m)	operation (N/m)
air	line pipe	800.1	800.1	800.1
	content	484.5	484.5	42.5
	coating	21.4	21.4	21.4
	piggyback	0.0	0.0	0.0
	coating pb	0.0	0.0	0.0
buoyancy	line pipe	613.4	613.4	613.4
	piggyback	0.0	0.0	0.0

$$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$$

$$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$$

Static & Dynamic span to be checked for the following environmental load combinations

Condition	Wave velocity	Current velocity	Comment
Installation	$H_{max,1yr}$	1 yr	
Hydrotest	$H_{max,1yr}$	1 yr	
Operational	$H_{max,100yr}$	10 yr	LC1
	$H_{max,10yr}$	100 yr	LC2

Environmental conditions

Water depths:

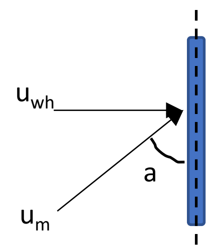
Seawater density		ρ_{sw} =	1025	kg/m³
Maximum water depth		WD_{max} =	40	m LAT
Minimum water depth		WD_{min} =	28.6	m LAT
Other water depth (user input)		WD =	28.6	m LAT
Storm surge, RP1 yr		ss_{1yr} =	-0.85	m LAT
Storm surge, RP10 yr		ss_{10yr} =	-1.02	m LAT
Storm surge, RP100 yr		ss_{100yr} =	-1.24	m LAT
Storm surge water level, RP1 yr	$SSWL_{1yr} = WD + ss_{1yr}$	$SSWL_{1yr}$ =	27.75	m LAT
Storm surge water level, RP10 yr	$SSWL_{10yr} = WD + ss_{10yr}$	$SSWL_{10yr}$ =	27.58	m LAT
Storm surge water level, RP100 yr	$SSWL_{100yr} = WD + ss_{100yr}$	$SSWL_{100yr}$ =	27.36	m LAT
Highest Astronomical Tide		HAT =	2.29	m

Waves (H_{max} & T_{max}):

Maximum wave height, RP1 yr - installation/hydrotest	$H_{max,1}$ =	11.3	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$ =	9.7	s
Maximum wave height, RP10 yr - operational	$H_{max,10}$ =	13.8	m
Associated maximum wave period, RP10 yr	$T_{ass,10}$ =	10.8	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$ =	16.2	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$ =	11.7	s

Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

	1 yr	10 yr	100 yr
$\frac{H}{g \cdot T_{ass}^2}$	0.0122	0.0121	0.0121
$\frac{SWL}{g \cdot T_{ass}^2}$	0.0301	0.0241	0.0204
theory	Stokes	Stokes	Stokes
maximum wave particle velocity (u_{wm})	2.03	2.79	3.51
angle of attack relative to P/L axis (a)	90	90	90
horizontal wave velocity ⊥ to P/L (u_{wh})	2.03	2.79	3.51



Current:

Height above seabed at which velocity is known	z* =	0.286	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.31	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.33	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	0.36	m/s

Current velocity at reference height: $U_{czr} = u_{st} + u_{ss}$

$U_{czr,1}$ =	0.31	m/s
$U_{czr,10}$ =	0.33	m/s
$U_{czr,100}$ =	0.36	m/s

Angle of attack relative to pipeline axis α_{uc} = 90 deg

Horizontal current velocity ⊥to P/L: $$u_{cm,perp} = \frac{7}{8} \cdot U_{czr} \cdot \left(\frac{OD_{nom}}{z_r}\right)^{1/7} \cdot \sin(\alpha_{uc})$$

$u_{cm,perp,1}$ =	0.269	m/s
$u_{cm,perp,10}$ =	0.287	m/s
$u_{cm,perp,100}$ =	0.313	m/s

Hydrodynamic coefficients:

Drag coefficient	C_D =	0.7	-
Lift coefficient	C_L =	0.9	-
Inertia coefficient	C_I =	3.29	-

Hydrodunamic forces:

Maximum absolute hydrodynamic force (F_D+F_I), RP1 yr (installation/hydrotest condition)	572	N/m
Maximum absolute hydrodynamic force (F_D+F_I), RP100/10 yr (LC 1 operational condition)	1484	N/m
Maximum absolute hydrodynamic force (F_D+F_I), RP10/100 yr (LC 2operational condition)	1001	N/m

Temperatures:

Ambient temperature T_{amb} = 10 deg. C

Table 3 - NEN 3656 load factors

Load factor	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
Self weight & content	1.1	1.1	1.1	1.1	
Coating	1.2	1.2	1.2	1.2	
Marine growth	0	0	1.2	1.2	
Internal pressure	0	1.15	1.15	1.15	
external pressure	1.1	1.1	1.1	1.1	
temperature	1	1.1	1.1	1.1	
environmental load	1.1	1.2	1.2	1.2	
Pipe bundle weight in air	1438.8	1438.8	952.6	952.6	N/m; incl. load factors
Submerged bundle weight, Ws	764.0	764.0	277.8	277.8	N/m; incl. load factors
Factored load acting on pipe, q	990	1027	1802	1233	N/m; $q = \sqrt{\gamma_W{}^2 \cdot W_S{}^2 + \gamma_H{}^2 \cdot (F_D + F_I)^2}$
Pressure	2	202	148	148	barg
DT	5	5	55	55	deg. C
Material factor (table 3; D3.1)	1.1	1.1	1.1	1.1	
Allowable stress (table 3; D3.1)	327.3	556.4	543.4	543.4	N/mm²

STATIC SPAN LENGTH - INSTALLATION

	Unrestrained pipe tension	Unrestrained pipe compression	Restrained pipe tension	Restrained pipe compression		
Hoop stress	4.6	4.6	4.6	4.6	N/mm²	$\sigma_H = \frac{(\gamma i \cdot Pi - \gamma e \cdot Pe) \cdot (OD - d_{min})}{2 \cdot d_{min}}$
Max. long. Stress	329.6	-324.9	329.6	-324.9	N/mm²	$\sigma_{max.long.stress} = \frac{\sigma_H \pm \sqrt{-3 \cdot \sigma_H^2 + 4 \cdot \sigma_{allow}^2}}{2}$
Long. hoop stress	2.0	2.0	1.4	1.4	N/mm²	$\sigma_{long.hoop.stress} = \nu \cdot \sigma_H$
Thermal exp. stress	n/a	n/a	-12.2	-12.2	N/mm²	$\sigma_{thermal} = -\gamma_t \cdot \alpha \cdot E_s \cdot \Delta T$
Max. allow. bending stress	327.3	-327.0	327.3	-314.1	N/mm²	$\sigma_{b,max} = \sigma_{max.long.stress} - \sigma_{lonh.hoop.stress} - \sigma_{thermal}$
Maximum span	46.2	46.2	46.2	45.3	m	

STATIC SPAN LENGTH - HYDROTEST

	Unrestrained pipe tension	Unrestrained pipe compression	Restrained pipe tension	Restrained pipe compression	
Hoop stress	336.2	336.2	336.2	336.2	N/mm²
Max. long. Stress	642.2	-306.0	642.2	-306.0	N/mm²
Long. hoop stress	103.1	103.1	100.8	100.8	N/mm²
Thermal exp. stress	n/a	n/a	-13.4	-13.4	N/mm²
Max. allow. bending stress	539.1	-409.1	554.7	-393.5	N/mm²
Maximum span	58.3	50.7	59.1	49.8	m

STATIC SPAN LENGTH - OPERATION LC1

	Unrestrained pipe tension	Unrestrained pipe compression	Restrained pipe tension	Restrained pipe compression	
Hoop stress	245.1	245.1	245.1	245.1	N/mm²
Max. long. Stress	622.8	-377.7	622.8	-377.7	N/mm²
Long. hoop stress	75.5	75.5	73.5	73.5	N/mm²
Thermal exp. stress	n/a	n/a	-147.4	-147.4	N/mm²
Max. allow. bending stress	543.4	-453.2	543.4	-303.8	N/mm²
Maximum span	44.2	40.3	44.2	33.0	m

STATIC SPAN LENGTH - OPERATION LC2

	Unrestrained pipe		Restrained pipe		
	tension	compression	tension	compression	
Hoop stress	245.1	245.1	245.1	245.1	N/mm^2
Max. long. Stress	622.8	-377.7	622.8	-377.7	N/mm^2
Long. hoop stress	75.5	75.5	73.5	73.5	N/mm^2
Thermal exp. stress	n/a	n/a	-147.4	-147.4	N/mm^2
Max. allow. bending stress	543.4	-453.2	543.4	-303.8	N/mm^2
Maximum span	53.4	48.8	53.4	39.9	m

DYNAMIC SPAN ANALYSIS (NEN 3656 - I.5.2.5)

Assessment Stability parameter, Ks < 1.8 => in-line vibration
Stability parameter, Ks < 16 => cross flow vibration

$$K_s = \frac{2m \times \delta}{\rho_w \times D_o^2}$$

Where,

d = damping factor water: 0.02 x 2 x π = 0.126 -
r_w = seawater density = 1025 kg/m³
D_o = outer diameter (incl. coating) = 278.7 mm
m = effective mass
m = W_{bundle} + M_{added}

$$M_{added} = \frac{\pi}{4} \cdot C_m \cdot \rho_w \cdot D_{o,eq}^2$$

C_m = added mass coefficient = 1.2 -
$D_{o,eq}$ = equivalent diameter (incl. coating) = 278.7 mm

Due to the presense of 2 objects attached to eachother, velocity flow intensification occurs:

v_{tot} = (v_{wave} + v_{cur}) x (1 + f_{int}); $f_{int} = \left\{1 + \left(\frac{D_{ob}^2}{4 \cdot CL^2}\right)\right\}$

Where,
D_{ob} = diameter of obstruction
CL = centerline distance P/L - obstruction

IN-LINE VIV:
Given the stability factor (Ks), the horizontal particle velocity (v), possibly including vicinity factor and the reduced velocity (Vr), the first eigen frequency (f1) can be determined prior to vibration occurring.

Reduced velocity, Vr, based on NEN 3656 I.5.2.5.2

$$V_r = \frac{V}{f_1 \times D_o}$$

if $1{,}0 \le V_r \le 3{,}5$ then oscillation occurs => Vr<1,0 design criterium

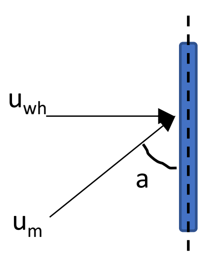
$$f_1 = \frac{a}{2\pi}\sqrt{\frac{E \times I}{m \times L^4}}$$

Where,
a = frequency factor (22 for fixed/fixed; 9.87 for pinned/pinned)
a = 15.4 for fixed/pinned a = 15.4

Waves (Hs & Tz):

Significant wave height, RP1 yr - installation/hydrotest	$H_{s,1}$ =	6.1	m
Associated wave period, RP1 yr	$T_{z,1}$ =	8.0	s
Significant wave height, RP10 yr - operational	$H_{s,10}$ =	7.5	m
Associated wave period, RP10 yr	$T_{z,10}$ =	8.9	s
Significant wave height, RP100 yr - operational	$H_{s,100}$ =	8.8	m
Associated wave period, RP100 yr	$T_{z,100}$ =	9.6	s

	1 yr	10 yr	100 yr
$\frac{H}{g \cdot T_{ass}^2}$	0.0097	0.0097	0.0097
$\frac{SWL}{g \cdot T_{ass}^2}$	0.0442	0.0355	0.0303
theory	Stokes	Stokes	Stokes
maximum wave particle velocity (u_{wm})	0.80	1.21	1.60
angle of attack relative to P/L axis (a)	90	90	90
horizontal wave velocity ⊥ to P/L (u_{wh})	0.80	1.21	1.60



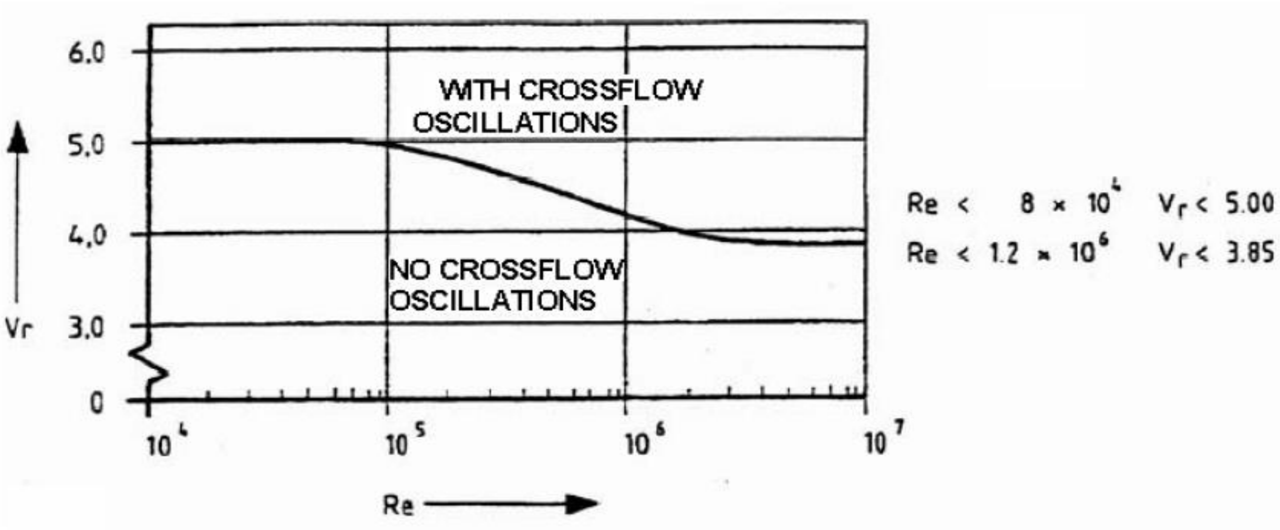
	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
effective mass	208.2	208.2	163.1	163.1	kg/m
K_s	0.66	0.66	0.51	0.51	-
In-line VIV	yes	yes	yes	yes	-
cross flow VIV	yes	yes	yes	yes	-
Vr	1.00	1.00	1.00	1.00	-
u_{wh}	0.80	0.80	1.60	1.21	m/s
$u_{cm,perp}$	0.27	0.27	0.29	0.31	m/s
D_{ob}	0.0	0.0	0.0	0.0	mm
CL	176.6	176.6	176.6	176.6	mm
f_{int}	0.000	0.000	0.000	0.000	-
$(u_{wh} + u_{cm,perp}) \times (1+0.5 \cdot f_{int}) = v_{tot}$	1.07	1.07	1.89	1.52	m/s
D_o	0.2787	0.2787	0.2787	0.2787	m
f1	3.84	3.84	6.77	5.46	1/s
$L_{span,in}$	13.8	13.8	11.0	12.3	m

note: f_{int} is taken into account for 50% as system doesn't instantaneously respond and vortices occur in a relatively steady state environment, which this isn't.

CROSS FLOW VIV:
Oscillation area for cross flow is given by the figure below and depends on the Reynolds number (R_e)

$$R_e = \frac{v \cdot D_o}{\nu_d}$$

v = horizontal particle velocity (v_{tot})
D_o = outer diameter (incl. coating) = 278.7 mm
u_d = dynamic viscosity seawater u_d = 4.99E-07 m^2/s



	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
u_{wh}	0.80	0.80	1.60	1.21	m/s
$u_{cm,perp}$	0.27	0.27	0.29	0.31	m/s
D_{ob}	0.0	0.0	0.0	0.0	mm
CL	176.6	176.6	176.6	176.6	mm
f_{int}	0.000	0.000	0.000	0.000	-
$(u_{wh} + u_{cm,perp}) \times (1+0.5 \cdot f_{int}) = v_{tot}$	1.07	1.07	1.89	1.52	m/s
D_o	0.2787	0.2787	0.2787	0.2787	m
Reynolds nr.	5.97E+05	5.97E+05	1.05E+06	8.51E+05	-
Vr	4.379	4.379	4.204	4.270	-
f1	0.88	0.88	1.61	1.28	1/s
$L_{span,cross}$	28.9	28.9	22.7	25.4	m

SUMMARY - SPAN ANALYSIS

	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
$L_{span,in}$	13.8	13.8	11.0	12.3	m
$L_{span,cross}$	28.9	28.9	22.7	25.4	m

Maximum Span Length = 11.0 m

Static & Dynamic Span - 10" x 12.7mm

Water depth	WD =	28.6	m (LAT)
Storm surge	ss =	-1.24	m
Storm surge water level	$SWL = WD + ss$ =	27.36	m
Wave height	H =	8.8	m
Wave period	T =	9.6	s
Grav. Acceleration	g =	9.81	m/s^2
Deep water wave length	$L_o = \frac{g \cdot T^2}{2 \cdot \pi}$ =	143.9	m

Solving for wave length (L) and λ

$$\frac{\pi \cdot H}{SWL} - \frac{L}{SWL}\left\{\lambda + \lambda^3 \cdot B_{33} + \lambda^5 \cdot (B_{35} + B_{55})\right\} = 0 \quad (\text{I})$$

$$\frac{SWL}{L_O} - \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) \cdot \left\{1 + \lambda^2 \cdot C_1 + \lambda^4 \cdot C_2\right\} = 0 \quad (\text{II})$$

Choosing L and solving for λ in (II) results in 4 roots for λ

Estimate actual wave length, L **132.240 m**

$$A = SWL / L_O = 0.1901$$

$$B = \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) = 0.1783$$

$$\lambda = \pm\sqrt{X}$$

$$X = \frac{-C_1 \cdot B \pm \sqrt{D}}{2 \cdot C_2 \cdot B}$$

$$D = (C_1 \cdot B)^2 - 4 \cdot (C_2 \cdot B) \cdot (-(A - B)) = 0.1076$$

	-	eq. (I)	eq. (II)
λ1	0.200	0.0000	0.0000
λ2	Numerator of X < 0		
λ3	-0.200	2.0209	0.0000
λ4	Numerator of X < 0		

Item	Formula	Value	Unit
s	$s = \sinh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.6983	-
c	$c = \cosh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.9709	-
A11	$A_{11} = \frac{1}{s} =$	0.5888	-
A13	$A_{13} = \frac{-c^2 \cdot (5 \cdot c^2 + 1)}{8 \cdot s^5} =$	-0.7018	-
	$A_{15} = -\frac{1184 \cdot c^{10} - 1440 \cdot c^8 - 1992 \cdot c^6 + 2641 \cdot c^4 - 249 \cdot c^2 + 18}{1536 \cdot s^{11}} =$	-1.2315	-
A22	$A_{22} = \frac{3}{8 \cdot s^4} =$	0.0451	-
A24	$A_{24} = \frac{192 \cdot c^8 - 424 \cdot c^6 - 312 \cdot c^4 + 480 \cdot c^2 - 17}{768 \cdot s^{10}} =$	0.1044	-
A33	$A_{33} = \frac{13 - 4 \cdot c^2}{64 \cdot s^7} =$	-0.0010	-
	$A_{35} = \frac{512 \cdot c^{12} + 4224 \cdot c^{10} - 6800 \cdot c^8 - 12808 \cdot c^6 + 16704 \cdot c^4 - 3154 \cdot c^2 - 107}{4096 \cdot s^{13} \cdot (6 \cdot c^2 - 1)} =$	0.0384	-
A44	$A_{44} = \frac{80 \cdot c^6 - 816 \cdot c^4 + 1338 \cdot c^2 - 197}{1536 \cdot s^{10} \cdot (6 \cdot c^2 - 1)} =$	-0.0004	-

$$A_{55} = -\frac{2880\cdot c^{10} - 72480\cdot c^{8} + 324000\cdot c^{6} - 432000\cdot c^{4} + 163470\cdot c^{2} - 16245}{61440\cdot s^{11}\cdot(6\cdot c^{2}-1)\cdot(8\cdot c^{4}-11\cdot c^{2}+3)} =$$ 0.0000 -

B22 $$B_{22} = \frac{(2\cdot c^{2}+1)\cdot c}{4\cdot s^{3}} =$$ 0.8820 -

B24 $$B_{24} = \frac{c\cdot(272\cdot c^{8} - 504\cdot c^{6} - 192\cdot c^{4} + 322\cdot c^{2} + 21)}{384\cdot s^{9}} =$$ 1.3430 -

B33 $$B_{33} = \frac{3\cdot(8\cdot c^{6}+1)}{64\cdot s^{6}} =$$ 0.9179 -

$$B_{35} = \frac{88128\cdot c^{14} - 208224\cdot c^{12} + 70848\cdot c^{10} + 54000\cdot c^{8} - 21816\cdot c^{6} + 6264\cdot c^{4} - 54\cdot c^{2} - 81}{12288\cdot s^{12}\cdot(6\cdot c^{2}-1)} =$$
= 3.3857 -

B44 $$B_{44} = c\cdot\frac{768\cdot c^{10} - 488\cdot c^{8} - 48\cdot c^{6} + 48\cdot c^{4} + 106\cdot c^{2} - 21}{384\cdot s^{9}\cdot(6\cdot c^{2}-1)} =$$ 1.1086 -

$$B_{55} = \frac{192000\cdot c^{16} - 26720\cdot c^{14} + 83680\cdot c^{12} + 20160\cdot c^{10} - 7280\cdot c^{8} + 7160\cdot c^{6} - 1800\cdot c^{4} - 1050\cdot c^{2} + 225}{12288\cdot s^{10}\cdot(8\cdot c^{4}-11\cdot c^{2}+3)\cdot(6\cdot c^{2}-1)} =$$
= 1.5232 -

C1 $$C_{1} = \frac{8\cdot c^{4} - 8\cdot c^{2} + 9}{8\cdot s^{4}} =$$ 1.4819 -

$$C_{2} = \frac{3840\cdot c^{12} - 4096\cdot c^{10} + 2592\cdot c^{8} - 1008\cdot c^{6} + 5944\cdot c^{4} - 1830\cdot c^{2} + 147}{512\cdot s^{10}\cdot(6\cdot c^{2}-1)} =$$ 4.4657 -

C3 $$C_{3} = -\frac{1}{4\cdot c\cdot s} =$$ -0.0747 -

C4 $$C_{4} = \frac{12\cdot c^{8} + 36\cdot c^{6} - 162\cdot c^{4} + 141\cdot c^{2} - 27}{192\cdot c\cdot s^{9}} =$$ 0.0656 -

K1 $$K_{1} = \lambda\cdot A_{11} + \lambda^{3}\cdot A_{13} + \lambda^{5}\cdot A_{15} =$$ 0.1118 -

K2	$K_2 = \lambda^2 \cdot A_{22} + \lambda^4 \cdot A_{24} =$	0.0020 -
K3	$K_3 = \lambda^3 \cdot A_{33} + \lambda^5 \cdot A_{35} =$	0.0000 -
K4	$K_4 = \lambda^4 \cdot A_{44} =$	0.0000 -
K5	$K_5 = \lambda^5 \cdot A_{55} =$	0.0000 -

Horizontal wave particle velocities

Water depth at which data required, z (w.r.t. seabed) 0.2731 m

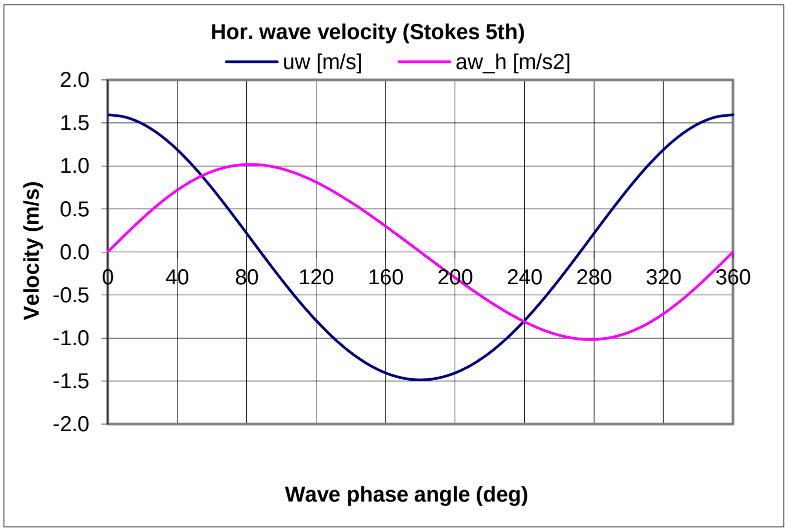
Horizontal velocity, u_w

$$u_w = \frac{L}{T} \cdot \sum_{n=1}^{5} n \cdot K_n \cdot \cosh\left(n \cdot \frac{2 \cdot \pi}{L} \cdot z\right) \cdot \cos(n \cdot \varphi)$$

Horizontal acceleration, $a_{w,h}$

$$a_{w,h} = \frac{2 \cdot \pi \cdot L}{T^2} \cdot \sum_{n=1}^{5} n^2 \cdot K_n \cdot \cosh\left(n \cdot \frac{2 \cdot \pi}{L} \cdot z\right) \cdot \sin(n \cdot \varphi)$$

ϕ [deg.]	uw [m/s]	aw_h [m/s^2]
0.00	1.5949	0.0000
10.00	1.5682	0.1995
20.00	1.4892	0.3908
30.00	1.3612	0.5660
40.00	1.1894	0.7184
50.00	0.9806	0.8426
60.00	0.7428	0.9348
70.00	0.4850	0.9930
80.00	0.2163	1.0170
90.00	-0.0544	1.0078
100.00	-0.3185	0.9682
110.00	-0.5683	0.9014
120.00	-0.7972	0.8114
130.00	-0.9994	0.7024
140.00	-1.1704	0.5783
150.00	-1.3068	0.4429
160.00	-1.4060	0.2995
170.00	-1.4661	0.1510
180.00	-1.4863	0.0000
190.00	-1.4661	-0.1510
200.00	-1.4060	-0.2995



210.00	-1.3068	-0.4429
220.00	-1.1704	-0.5783
230.00	-0.9994	-0.7024
240.00	-0.7972	-0.8114
250.00	-0.5683	-0.9014
260.00	-0.3185	-0.9682
270.00	-0.0544	-1.0078
280.00	0.2163	-1.0170
290.00	0.4850	-0.9930
300.00	0.7428	-0.9348
310.00	0.9806	-0.8426
320.00	1.1894	-0.7184
330.00	1.3612	-0.5660
340.00	1.4892	-0.3908
350.00	1.5682	-0.1995
360.00	1.5949	0.0000

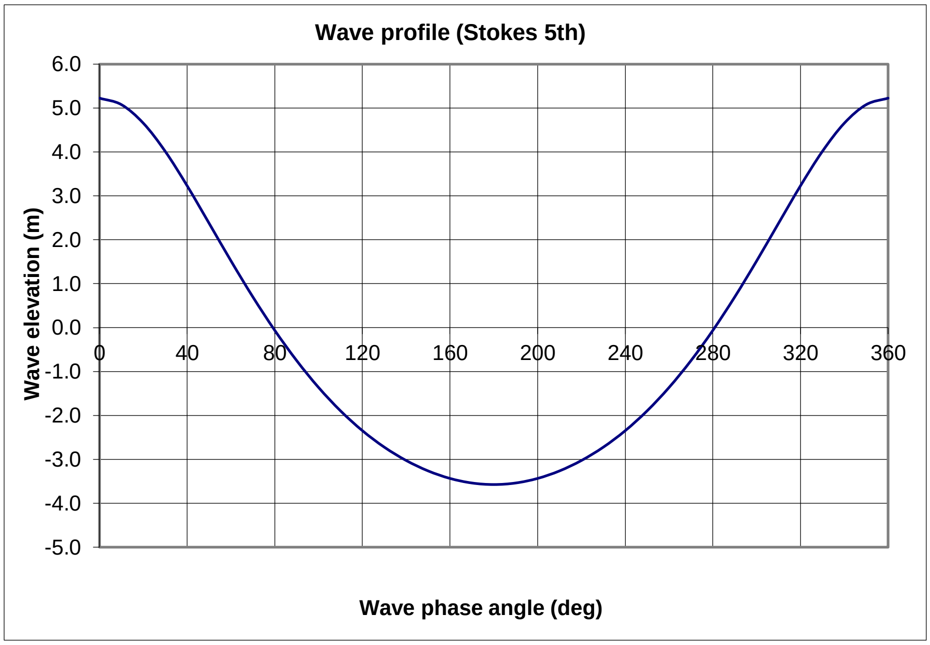
U_{wm} = max. wave particle velocity = 1.59 m/s

Originator	: PF	Checked	: VH
Date	: 16.07.2018		
Revision	: 01		

Wave profile h(t)

$$\eta(t)=\frac{L}{2\cdot\pi}\{\lambda\cdot\cos(\varphi)+(\lambda^2\cdot B_{22}+\lambda^4\cdot B_{24})\cdot\cos(2\varphi)+(\lambda^3\cdot B_{33}+\lambda^5\cdot B_{35})\cdot\cos(3\varphi)+\lambda^4\cdot B_{44}\cdot\cos(4\varphi)+\lambda^5\cdot B_{55}\cdot\cos(5\varphi)\}$$

φ (deg.)	η(t) (m)
0.00	5.2262
10.00	5.0784
20.00	4.6557
30.00	4.0144
40.00	3.2298
50.00	2.3778
60.00	1.5203
70.00	0.6991
80.00	-0.0621
90.00	-0.7514
100.00	-1.3630
110.00	-1.8946
120.00	-2.3465
130.00	-2.7221
140.00	-3.0262
150.00	-3.2631
160.00	-3.4343
170.00	-3.5386
180.00	-3.5737
190.00	-3.5386
200.00	-3.4343
210.00	-3.2631
220.00	-3.0262
230.00	-2.7221
240.00	-2.3465
250.00	-1.8946
260.00	-1.3630
270.00	-0.7514
280.00	-0.0621
290.00	0.6991
300.00	1.5203
310.00	2.3778
320.00	3.2298
330.00	4.0144
340.00	4.6557
350.00	5.0784
360.00	5.2262



Originator : PF
Date : 16.07.2018
Revision : 01
Checked : VH

Static & Dynamic Span - 10" x 12.7mm

(adjusted) Drag coefficient, C_D	0.7	-
(adjusted) Lift coefficient, C_L	0.9	-
(adjusted) Inertia coefficient, C_I	3.29	-
Sea water density, ρ_{sw}	1025	kg/m^3
Total OD pipeline, OD_tot (or equivalent bundle diameter)	278.7	mm
Angle of attack relative to pipeline axis, wave	90	deg
Wave forces based on	**Stokes**	**theory**
Current	**1 yr**	

ϕ [deg]	u_{w_perp} [m/s]	u_{cm_perp} [m/s]	u_{tot_perp} [m/s]	Fd [N/m]	Fl [N/m]
0.00	1.59	0.27	1.86	347.5	446.8
10.00	1.57	0.27	1.84	337.7	434.1
20.00	1.49	0.27	1.76	309.3	397.6
30.00	1.36	0.27	1.63	265.9	341.8
40.00	1.19	0.27	1.46	212.8	273.6
50.00	0.98	0.27	1.25	156.2	200.9
60.00	0.74	0.27	1.01	102.5	131.7
70.00	0.49	0.27	0.75	56.9	73.2
80.00	0.22	0.27	0.49	23.6	30.3
90.00	-0.05	0.27	0.22	4.6	5.9
100.00	-0.32	0.27	-0.05	-0.2	0.3
110.00	-0.57	0.27	-0.30	-8.9	11.5
120.00	-0.80	0.27	-0.53	-27.8	35.8
130.00	-1.00	0.27	-0.73	-53.3	68.5
140.00	-1.17	0.27	-0.90	-81.2	104.4
150.00	-1.31	0.27	-1.04	-107.6	138.3
160.00	-1.41	0.27	-1.14	-129.1	166.0
170.00	-1.47	0.27	-1.20	-143.2	184.1
180.00	-1.49	0.27	-1.22	-148.0	190.3
190.00	-1.47	0.27	-1.20	-143.2	184.1
200.00	-1.41	0.27	-1.14	-129.1	166.0
210.00	-1.31	0.27	-1.04	-107.6	138.3
220.00	-1.17	0.27	-0.90	-81.2	104.4
230.00	-1.00	0.27	-0.73	-53.3	68.5
240.00	-0.80	0.27	-0.53	-27.8	35.8
250.00	-0.57	0.27	-0.30	-8.9	11.5
260.00	-0.32	0.27	-0.05	-0.2	0.3
270.00	-0.05	0.27	0.22	4.6	5.9
280.00	0.22	0.27	0.49	23.6	30.3
290.00	0.49	0.27	0.75	56.9	73.2
300.00	0.74	0.27	1.01	102.5	131.7
310.00	0.98	0.27	1.25	156.2	200.9
320.00	1.19	0.27	1.46	212.8	273.6
330.00	1.36	0.27	1.63	265.9	341.8

340.00	1.49	0.27	1.76	309.3	397.6
350.00	1.57	0.27	1.84	337.7	434.1
360.00	1.59	0.27	1.86	347.5	446.8

ϕ	a_{w_h}	$a_{w\_h\_perp}$	Fi	Fd+Fi	ABS(Fd+Fi)
[deg]	[m/s^2]	[m/s^2]	[N/m]	[N/m]	[N/m]
0.00	0.00	0.00	0.0	347.5	347.5
10.00	0.20	0.20	41.0	378.7	378.7
20.00	0.39	0.39	80.4	389.6	389.6
30.00	0.57	0.57	116.4	382.3	382.3
40.00	0.72	0.72	147.8	360.6	360.6
50.00	0.84	0.84	173.3	329.6	329.6
60.00	0.93	0.93	192.3	294.8	294.8
70.00	0.99	0.99	204.3	261.2	261.2
80.00	1.02	1.02	209.2	232.8	232.8
90.00	1.01	1.01	207.3	212.0	212.0
100.00	0.97	0.97	199.2	198.9	198.9
110.00	0.90	0.90	185.4	176.5	176.5
120.00	0.81	0.81	166.9	139.1	139.1
130.00	0.70	0.70	144.5	91.2	91.2
140.00	0.58	0.58	119.0	37.8	37.8
150.00	0.44	0.44	91.1	-16.5	16.5
160.00	0.30	0.30	61.6	-67.5	67.5
170.00	0.15	0.15	31.1	-112.1	112.1
180.00	0.00	0.00	0.0	-148.0	148.0
190.00	-0.15	-0.15	-31.1	-174.2	174.2
200.00	-0.30	-0.30	-61.6	-190.8	190.8
210.00	-0.44	-0.44	-91.1	-198.7	198.7
220.00	-0.58	-0.58	-119.0	-200.1	200.1
230.00	-0.70	-0.70	-144.5	-197.8	197.8
240.00	-0.81	-0.81	-166.9	-194.8	194.8
250.00	-0.90	-0.90	-185.4	-194.4	194.4
260.00	-0.97	-0.97	-199.2	-199.4	199.4
270.00	-1.01	-1.01	-207.3	-202.7	202.7
280.00	-1.02	-1.02	-209.2	-185.6	185.6
290.00	-0.99	-0.99	-204.3	-147.4	147.4
300.00	-0.93	-0.93	-192.3	-89.9	89.9
310.00	-0.84	-0.84	-173.3	-17.1	17.1
320.00	-0.72	-0.72	-147.8	65.0	65.0
330.00	-0.57	-0.57	-116.4	149.4	149.4
340.00	-0.39	-0.39	-80.4	228.9	228.9
350.00	-0.20	-0.20	-41.0	296.6	296.6
360.00	0.00	0.00	0.0	347.5	347.5

Maximum absolute hydrodynamic force 389.6 N/m

APPENDIX D Upheaval Buckling Calculations

D.1 Upheaval Buckling – pressure = 148 barg; temperature = 65 deg. C

D.2 Upheaval Buckling – pressure = 148 barg; temperature = 40 deg. C

D.1 UHB Analysis – 65 deg. C

(4 pages)

Client	: Wintershall		
Project	: D12-B to D15-FA-1 pipeline		
Project No.	: 18004		
Subject	: Pipeline Upheaval Buckling - analytical		
Doc. No.	: 18004-60-CAL-01506-01		
Client Doc. No.	: D12B-67031002-PL-LA0580-GLOBAL-009		
Calc'd by	: EvW	**Rev.**	: 01
Checked	:	**Date**	: 24/08/2018

Upheaval buckling calculation

Pipe data

Outside pipe diameter		OD_s =	273.1	mm
Pipe wall thickness		t_s =	12.7	mm
Internal pipe diameter	$= OD\_s - 2 \cdot t\_s$	ID_s =	247.7	mm

Steel data

Material			L360NB	
Density steel		ρ_s =	7850	kg/m^3
Young's modulus		E_s =	206000	N/mm^2
Poisson's ratio		ν =	0.3	-
Thermal expansion coefficient		α =	1.17E-05	m/m/°C
Steel area	$= \frac{1}{4} \cdot \pi \cdot (OD^2\_s - ID^2\_s)$	A_s =	10389.5	mm^2
Internal pipe area	$= \frac{1}{4} \cdot \pi \cdot ID^2\_s$	A_i =	4.82E+04	mm^2
Moment of inertia	$= \frac{\pi}{64} \cdot (OD^4\_s - ID^4\_s)$	I_s =	8.83E+07	mm^4
Pipe weight in air		W_{pe} =	81.6	kg/m
Sea water density		r_{sw} =	1025	kg/m^3
Pipeline contents density		r_{cont} =	25	kg/m^3

Internal lining

Thickness		t_l =	0	mm
Density		r_l =	0	kg/m^3
Lining weight		W_l =	0.0	kg/m

Coating data

Outer coating layer 1

Thickness		t_{c1} =	2.8	mm
Density		ρ_{c1} =	900	kg/m^3
Layer 1 weight	$W_{l1} = \frac{\pi}{4} \cdot \{(OD + 2 \cdot t_{c1})^2 - OD^2\} \cdot \rho_{c1}$	W_{l1} =	2.2	kg/m

Weight piggy back line

Piggy back weight		W_{l2} =	0.0	kg/m

Concrete coating

Thickness		t_{con} =	0	mm
Density		ρ_{con} =	0	kg/m^3
Concrete weight	$W_{con} = \frac{\pi}{4} \cdot \{(OD + 2 \cdot t_{c1} + 2 \cdot t_{c2} + 2 \cdot t_{con})^2 - (OD + 2 \cdot t_{c1} + 2 \cdot t_{c2})^2\} \cdot \rho_{con}$	W_{con} =	0.0	kg/m

Client	: Wintershall		
Project	: D12-B to D15-FA-1 pipeline		
Project No.	: 18004		
Subject	: Pipeline Upheaval Buckling - analytical		
Doc. No.	: 18004-60-CAL-01506-01		
Client Doc. No.	: D12B-67031002-PL-LA0580-GLOBAL-009		
Calc'd by	: EvW	**Rev.**	: 01
Checked	:	**Date**	: 24/08/2018

Marine growth

Thickness		t_{mg} =	0	mm
Density		ρ_{mg} =	0	kg/m^3
Marine growth weight	$W_{mg} = \pi/4 \cdot \{(OD + 2\cdot t_{c1} + 2\cdot t_{c2} + 2\cdot t_{con} + 2\cdot t_{mg})^2 - (OD + 2\cdot t_{c1} + 2\cdot t_{c2} + 2\cdot t_{con})^2\} \cdot \rho_{mg}$	W_{mg} =	0.0	kg/m

Weight data

Total outside diameter	$ODtot = OD + 2\cdot t \cdot + 2\cdot t_{c2} + 2\cdot t_{con} + 2\cdot t_{mg}$	OD_{tot} =	278.7	mm
Contents weight	$W_{cont} = \pi/4 \cdot (ID - 2\cdot t_l)^2 \cdot \rho_{cont}$	W_{cont} =	1.2	kg/m
Pipeline weight in air	$w_r = w_{pe} + w_l + w_{l1} + w_{l2} + w_{con} + w_{mg} + w_{cont}$	W_r =	84.9	kg/m
Buoyancy force, F_B	$F_B = \pi/4 \cdot OD_{tot}^2 \cdot \rho_w$	F_B =	62.5	kg/m
Submerged pipeline weight, W_{sm}	$W_{sm} = W_r - F_B$	W_{sm} =	22.4	kg/m

Soil data

Submerged soil cover density		γ' =	850	kg/m^3
Angle of internal friction		ϕ_{soil} =	30	deg.
Potyondy coeff. Soil		p_{soil} =	0.6	-
Height soil cover from top of pipe		H =	1.3	m
Soil uplift coefficient		f_{soil} =	0.2	-

(0.5 for dense materials and 0.1 for loose materials)

Soil weight on top of pipe	$q = \gamma' \cdot H \cdot OD_{tot} \cdot (1 + f \cdot H / OD_{tot})$	q =	5839.5	N/m
Imperfection height		δ =	1000	mm

Pressure data

Design pressure		P_d =	148	barg
Maximum operating pressure		P_i =	60	barg
Minimum external pressure		P_e =	2.5	barg

Temperature data

Seawater temperature, T_{sea}		T_{sea} =	3	^{o}C
Temperature of gas, T_{gas}		T_{gas} =	65	^{o}C

Pipeline forces

Compressive temperature force, F_T	$F_T = E \cdot A \cdot \alpha \cdot (T_{gas} - T_{sea})$	F_T =	1552527.7	N
Tensile Poisson force, F_P	$F_P = A_i \cdot \nu \cdot \frac{\{P_D - P_e\} \cdot OD_s}{2 \cdot t}$	F_P =	487603.5	N
Compressive member end force, F_e	$F_e = \{P_D - P_e\} \cdot \pi/4 \cdot ID_s^2$	F_e =	701140.2	N
Is area under considerations within anchor zone (y/n) ?		=	n	

(y: F_T can be neglected)

Effective compressive axial force, F_{eff}	$F_{eff} = F_T - F_P + F_e$	F_{eff} =	1766064.4	N

Client	: Wintershall		
Project	: D12-B to D15-FA-1 pipeline		
Project No.	: 18004		
Subject	: Pipeline Upheaval Buckling - analytical		
Doc. No.	: 18004-60-CAL-01506-01		
Client Doc. No.	: D12B-67031002-PL-LA0580-GLOBAL-009		
Calc'd by	: EvW	**Rev.**	: 01
Checked	:	**Date**	: 24/08/2018

Required down load

The required download depends on:

- dimensionless maximum download parameter, F_W
- dimensionless imperfection length parameter, F_L

$$\Phi_W = \frac{w \cdot EI}{\delta \cdot F_{eff}^2} \quad \text{and} \quad \Phi_L = L \cdot \sqrt{\frac{F_{eff}}{EI}}$$

where,

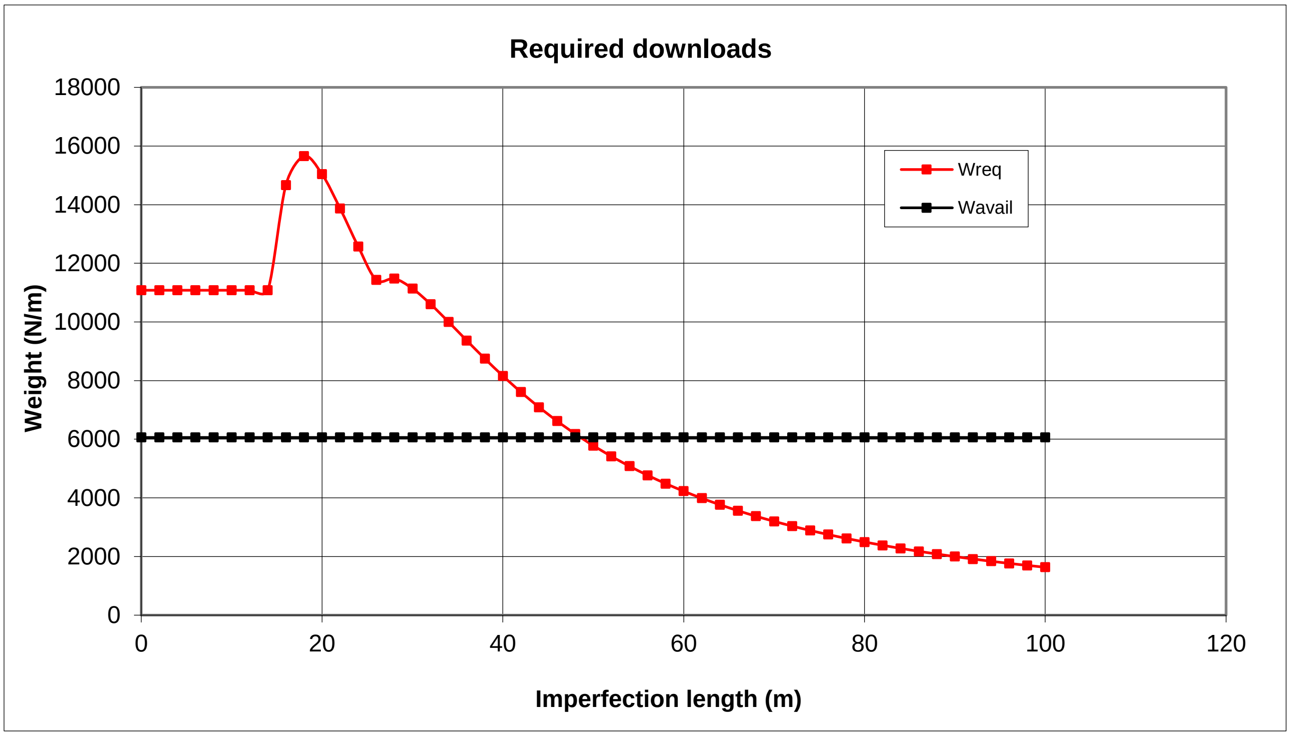
F_W = dimensionless maximum download parameter
w = required download (N/mm)
F_{eff} = effective axial force (N)
EI = bending stiffness pipeline (N/mm^2)
d = imperfection height (mm)
F_L = dimensionless imperferction length parameter
L = imperfection / exposure length (mm)

Requirements:

$$\Phi_L \le 4.49 \qquad \Phi_W = 0.0646$$
$$4.49 < \Phi_L \le 8.06 \qquad \Phi_W = 5.68 / \Phi_L^2 - 88.35 / \Phi_L^4$$
$$\Phi_L > 8.06 \qquad \Phi_W = 9.6 / \Phi_L^2 - 343 / \Phi_L^4$$

L [m]	F_L	F_W	W_{req} [N/m]	W_{avail} [N/m]
0	0.000	0.0646	11080.517	6059
2	0.623	0.0646	11080.517	6059
4	1.247	0.0646	11080.517	6059
6	1.870	0.0646	11080.517	6059
8	2.493	0.0646	11080.517	6059
10	3.116	0.0646	11080.517	6059
12	3.740	0.0646	11080.517	6059
14	4.363	0.0646	11080.517	6059
16	4.986	0.0855	14670.666	6059
18	5.610	0.0913	15656.736	6059
20	6.233	0.0877	15037.226	6059
22	6.856	0.0808	13867.653	6059
24	7.479	0.0733	12573.108	6059
26	8.103	0.0666	11431.662	6059
28	8.726	0.0669	11478.047	6059
30	9.349	0.0649	11137.950	6059
32	9.973	0.0618	10608.733	6059
34	10.596	0.0583	9998.997	6059
36	11.219	0.0546	9368.576	6059
38	11.843	0.0510	8749.949	6059
40	12.466	0.0476	8160.036	6059
42	13.089	0.0443	7606.843	6059
44	13.712	0.0414	7093.284	6059
46	14.336	0.0386	6619.399	6059
48	14.959	0.0361	6183.664	6059
50	15.582	0.0337	5783.758	6059
52	16.206	0.0316	5417.017	6059
54	16.829	0.0296	5080.696	6059

56	17.452	0.0278	4772.118	6059
58	18.075	0.0262	4488.751	6059
60	18.699	0.0247	4228.251	6059
62	19.322	0.0233	3988.469	6059
64	19.945	0.0220	3767.456	6059
66	20.569	0.0208	3563.450	6059
68	21.192	0.0197	3374.865	6059
70	21.815	0.0187	3200.275	6059
72	22.438	0.0177	3038.403	6059
74	23.062	0.0168	2888.100	6059
76	23.685	0.0160	2748.337	6059
78	24.308	0.0153	2618.189	6059
80	24.932	0.0146	2496.825	6059
82	25.555	0.0139	2383.497	6059
84	26.178	0.0133	2277.534	6059
86	26.801	0.0127	2178.328	6059
88	27.425	0.0122	2085.332	6059
90	28.048	0.0116	1998.051	6059
92	28.671	0.0112	1916.036	6059
94	29.295	0.0107	1838.881	6059
96	29.918	0.0103	1766.217	6059
98	30.541	0.0099	1697.709	6059
100	31.165	0.0095	1633.051	6059



D.2 UHB Analysis – 40 deg. C

(4 pages)

Client	: Wintershall		
Project	: D12-B to D15-FA-1 pipeline		
Project No.	: 18004		
Subject	: Pipeline Upheaval Buckling - analytical		
Doc. No.	: 18004-60-CAL-01506-01		
Client Doc. No.	: D12B-67031002-PL-LA0580-GLOBAL-009		
Calc'd by	: EvW	**Rev.**	: 01
Checked	:	**Date**	: 24/08/2018

Upheaval buckling calculation

Pipe data

Outside pipe diameter		OD_s =	273.1	mm
Pipe wall thickness		t_s =	12.7	mm
Internal pipe diameter	$= OD\_s - 2 \cdot t\_s$	ID_s =	247.7	mm

Steel data

Material			L360NB	
Density steel		ρ_s =	7850	kg/m^3
Young's modulus		E_s =	206000	N/mm^2
Poisson's ratio		ν =	0.3	-
Thermal expansion coefficient		α =	1.17E-05	m/m/°C
Steel area	$= \frac{1}{4} \cdot \pi \cdot (OD^2\_s - ID^2\_s)$	A_s =	10389.5	mm^2
Internal pipe area	$= \frac{1}{4} \cdot \pi \cdot ID^2\_s$	A_i =	4.82E+04	mm^2
Moment of inertia	$= \frac{\pi}{64} \cdot (OD^4\_s - ID^4\_s)$	I_s =	8.83E+07	mm^4
Pipe weight in air		W_{pe} =	81.6	kg/m
Sea water density		r_{sw} =	1025	kg/m^3
Pipeline contents density		r_{cont} =	25	kg/m^3

Internal lining

Thickness		t_l =	0	mm
Density		r_l =	0	kg/m^3
Lining weight		W_l =	0.0	kg/m

Coating data

Outer coating layer 1

Thickness		t_{c1} =	2.8	mm
Density		ρ_{c1} =	900	kg/m^3
Layer 1 weight	$W_{l1} = \frac{\pi}{4} \cdot \{(OD + 2 \cdot t_{c1})^2 - OD^2\} \cdot \rho_{c1}$	W_{l1} =	2.2	kg/m

Weight piggy back line

Piggy back weight		W_{l2} =	0.0	kg/m

Concrete coating

Thickness		t_{con} =	0	mm
Density		ρ_{con} =	0	kg/m^3
Concrete weight	$W_{con} = \frac{\pi}{4} \cdot \{(OD + 2 \cdot t_{c1} + 2 \cdot t_{c2} + 2 \cdot t_{con})^2 - (OD + 2 \cdot t_{c1} + 2 \cdot t_{c2})^2\} \cdot \rho_{con}$	W_{con} =	0.0	kg/m

Client	: Wintershall
Project	: D12-B to D15-FA-1 pipeline
Project No.	: 18004
Subject	: Pipeline Upheaval Buckling - analytical
Doc. No.	: 18004-60-CAL-01506-01
Client Doc. No.	: D12B-67031002-PL-LA0580-GLOBAL-009

enersea®

Calc'd by	: EvW	**Rev.**	: 01
Checked	:	**Date**	: 24/08/2018

Marine growth

Thickness		t_{mg} =	0	mm
Density		ρ_{mg} =	0	kg/m^3
Marine growth weight	$W_{mg} = \pi/4 \cdot \{(OD + 2 \cdot t_{c1} + 2 \cdot t_{c2} + 2 \cdot t_{con} + 2 \cdot t_{mg})^2 - (OD + 2 \cdot t_{c1} + 2 \cdot t_{c2} + 2 \cdot t_{con})^2\} \cdot \rho_{mg}$	W_{mg} =	0.0	kg/m

Weight data

Total outside diameter	$ODtot = OD + 2 \cdot t \cdot + 2 \cdot t_{c2} + 2 \cdot t_{con} + 2 \cdot t_{mg}$	OD_{tot} =	278.7	mm
Contents weight	$W_{cont} = \pi/4 \cdot (ID - 2 \cdot t_l)^2 \cdot \rho_{cont}$	W_{cont} =	1.2	kg/m
Pipeline weight in air	$w_r = w_{pe} + w_l + w_{l1} + w_{l2} + w_{con} + w_{mg} + w_{cont}$	W_r =	84.9	kg/m
Buoyancy force, F_B	$F_B = \pi/4 \cdot OD_{tot}^2 \cdot \rho_w$	F_B =	62.5	kg/m
Submerged pipeline weight, W_{sm}	$W_{sm} = W_r - F_B$	W_{sm} =	22.4	kg/m

Soil data

Submerged soil cover density		γ' =	850	kg/m^3
Angle of internal friction		ϕ_{soil} =	30	deg.
Potyondy coeff. Soil		p_{soil} =	0.6	-
Height soil cover from top of pipe		H =	1.3	m
Soil uplift coefficient		f_{soil} =	0.2	-

(0.5 for dense materials and 0.1 for loose materials)

Soil weight on top of pipe	$q = \gamma' \cdot H \cdot OD_{tot} \cdot (1 + f \cdot H / OD_{tot})$	q =	5839.5	N/m
Imperfection height		δ =	1000	mm

Pressure data

Design pressure	P_d =	148	barg
Maximum operating pressure	P_i =	60	barg
Minimum external pressure	P_e =	2.5	barg

Temperature data

Seawater temperature, T_{sea}	T_{sea} =	3	^{o}C
Temperature of gas, T_{gas}	T_{gas} =	40	^{o}C

Pipeline forces

Compressive temperature force, F_T	$F_T = E \cdot A \cdot \alpha \cdot (T_{gas} - T_{sea})$	F_T =	926508.4	N
Tensile Poisson force, F_P	$F_P = A_i \cdot \nu \cdot \frac{\{P_D - P_e\} \cdot OD_s}{2 \cdot t}$	F_P =	487603.5	N
Compressive member end force, F_e	$F_e = \{P_D - P_e\} \cdot \pi/4 \cdot ID_s^2$	F_e =	701140.2	N
Is area under considerations within anchor zone (y/n) ?		=	n	

(y: F_T can be neglected)

Effective compressive axial force, F_{eff}	$F_{eff} = F_T - F_P + F_e$	F_{eff} =	1140045.2	N

Client	: Wintershall			
Project	: D12-B to D15-FA-1 pipeline			
Project No.	: 18004			
Subject	: Pipeline Upheaval Buckling - analytical			
Doc. No.	: 18004-60-CAL-01506-01			
Client Doc. No.	: D12B-67031002-PL-LA0580-GLOBAL-009			
Calc'd by	: EvW		**Rev.**	: 01
Checked	:		**Date**	: 24/08/2018

Required down load

The required download depends on:

- dimensionless maximum download parameter, F_W
- dimensionless imperfection length parameter, F_L

$$\Phi_W = \frac{w \cdot EI}{\delta \cdot F_{eff}^2} \quad \text{and} \quad \Phi_L = L \cdot \sqrt{\frac{F_{eff}}{EI}}$$

where,

F_W = dimensionless maximum download parameter
w = required download (N/mm)
F_{eff} = effective axial force (N)
EI = bending stiffness pipeline (N/mm^2)
d = imperfection height (mm)
F_L = dimensionless imperferction length parameter
L = imperfection / exposure length (mm)

Requirements:

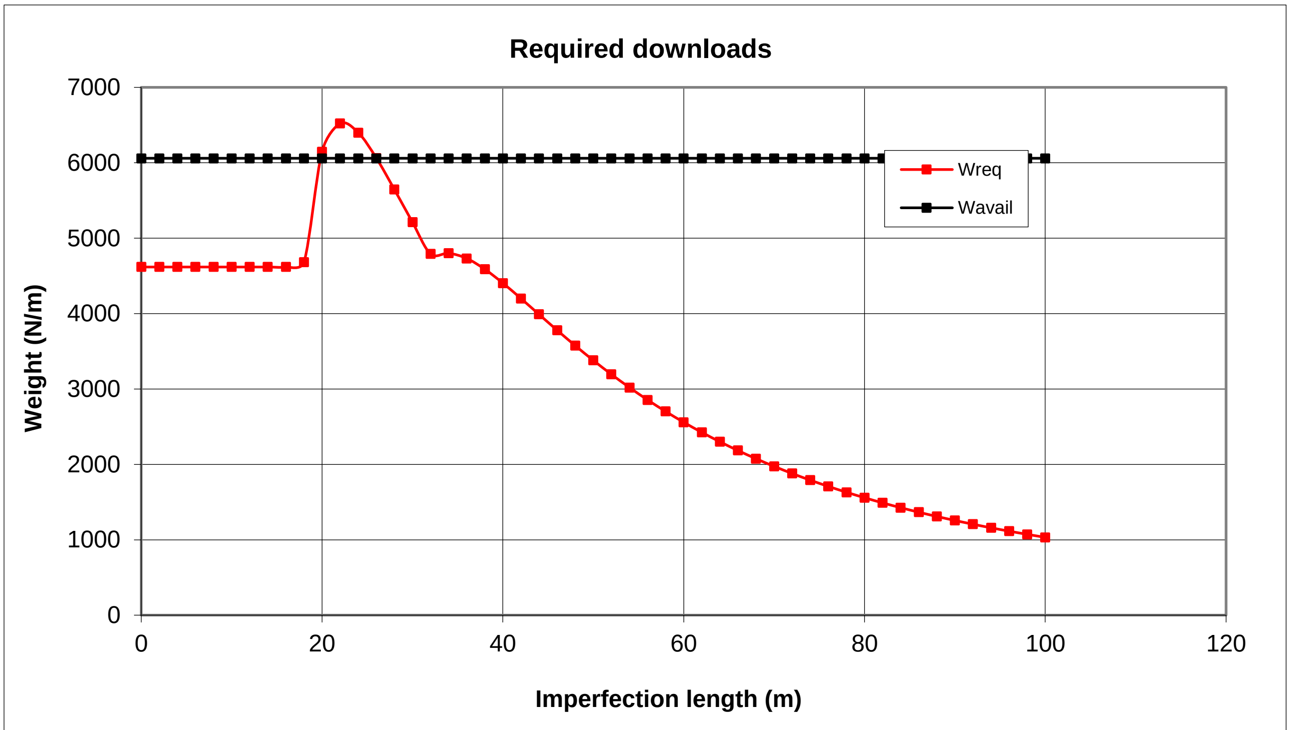
$$\Phi_L \le 4.49 \qquad \Phi_W = 0.0646$$
$$4.49 < \Phi_L \le 8.06 \qquad \Phi_W = 5.68/\Phi_L^2 - 88.35/\Phi_L^4$$
$$\Phi_L > 8.06 \qquad \Phi_W = 9.6/\Phi_L^2 - 343/\Phi_L^4$$

L [m]	F_L	F_W	W_{req} [N/m]	W_{avail} [N/m]
0	0.000	0.0646	4617.332	6059
2	0.501	0.0646	4617.332	6059
4	1.002	0.0646	4617.332	6059
6	1.502	0.0646	4617.332	6059
8	2.003	0.0646	4617.332	6059
10	2.504	0.0646	4617.332	6059
12	3.005	0.0646	4617.332	6059
14	3.505	0.0646	4617.332	6059
16	4.006	0.0646	4617.332	6059
18	4.507	0.0655	4682.078	6059
20	5.008	0.0860	6147.753	6059
22	5.509	0.0912	6520.981	6059
24	6.009	0.0895	6399.863	6059
26	6.510	0.0848	6063.484	6059
28	7.011	0.0790	5645.785	6059
30	7.512	0.0729	5211.566	6059
32	8.013	0.0670	4791.570	6059
34	8.513	0.0672	4800.222	6059
36	9.014	0.0662	4731.397	6059
38	9.515	0.0642	4588.049	6059
40	10.016	0.0616	4403.921	6059
42	10.516	0.0588	4199.936	6059
44	11.017	0.0558	3989.057	6059
46	11.518	0.0529	3779.237	6059
48	12.019	0.0500	3575.251	6059
50	12.520	0.0473	3379.844	6059
52	13.020	0.0447	3194.464	6059
54	13.521	0.0422	3019.728	6059

Client	: Wintershall
Project	: D12-B to D15-FA-1 pipeline
Project No.	: 18004
Subject	: Pipeline Upheaval Buckling - analytical
Doc. No.	: 18004-60-CAL-01506-01
Client Doc. No.	: D12B-67031002-PL-LA0580-GLOBAL-009

Calc'd by	: EvW	**Rev.**	: 01
Checked	:	**Date**	: 24/08/2018

56	14.022	0.0400	2855.732	6059
58	14.523	0.0378	2702.252	6059
60	15.023	0.0358	2558.866	6059
62	15.524	0.0339	2425.050	6059
64	16.025	0.0322	2300.223	6059
66	16.526	0.0306	2183.793	6059
68	17.027	0.0290	2075.171	6059
70	17.527	0.0276	1973.789	6059
72	18.028	0.0263	1879.108	6059
74	18.529	0.0251	1790.623	6059
76	19.030	0.0239	1707.862	6059
78	19.530	0.0228	1630.387	6059
80	20.031	0.0218	1557.796	6059
82	20.532	0.0208	1489.716	6059
84	21.033	0.0199	1425.807	6059
86	21.534	0.0191	1365.756	6059
88	22.034	0.0183	1309.275	6059
90	22.535	0.0176	1256.102	6059
92	23.036	0.0169	1205.995	6059
94	23.537	0.0162	1158.733	6059
96	24.038	0.0156	1114.113	6059
98	24.538	0.0150	1071.950	6059
100	25.039	0.0144	1032.073	6059



APPENDIX E. Cathodic Protection Design Calculations

E.1 Cathodic Protection Design Calculation

Project	:	**D12-B Pipeline detailed design**
Project #	:	18004.500
Subject	:	Cathodic Protection Calculation
File #	:	18004-60-CAL-01503-01
Client	:	Wintershall
Client File #	:	D12B-67031002-PL-LA0580-GLOBAL-004
Originator	:	JM
Date	:	16-8-2018
Revision	:	02

Checked :

Pipeline cathodic protection

General:				
Design life			30	yrs
Anode Type			Bracelet Half-shell type	
Utilization factor	u	=	0,8	
Pipeline data:				
Outside diameter of pipeline	OD	=	273,1	mm
Wall thickness	t_w	=	12,7	mm
Coating thickness		=	2,8	mm
Anode thickness		=	38	mm
Buried / Submerged			Buried	
Environmental data:				
Maximum fluid design temperature	Tmax	=	60	°C
Piggyback data:				
Outside diameter of pipeline	OD	=	0	mm
Wall thickness	t_w	=	0	mm
Coating thickness		=	0	mm
Coating				
Initial coating deficiency		=	0	
Anode:				
Type:		=	Al	
Anode density		=	2700	kg/m^3
Bracelet		=	1	x half shell
Internal diameter		=	278,7	mm
Maximum thickness		=	38	mm
Initial anode diameter	D_{ani}	=	354,7	mm
Anode length	L_{an}	=	323	mm
Initial anode outside surface	A_{ani}	=	0,360	m^2
Final anode outside surface	A_{anf}	=	0,298	m^2
Initial net anode weight (half bracelet)	m_a	=	16,5	kg

Pipeline cathodic protection

General:

Design life	t_f	=	30	yrs
Utilization factor	u	=	0,8	

Pipeline data:

Outside diameter of pipeline	OD	=	273,1	mm
Wall thickness	t_w	=	12,7	mm
Coating thickness		=	2,8	mm
Anode thickness		=	38	mm
Buried or Submerged			Buried	

Piggyback data:

Outside diameter of pipeline	OD	=	0	mm
Wall thickness	t_w	=	0	mm
Coating thickness		=	0	mm

Linepipe:

Factory applied coating type	select	Three-layer coating systems (3LPE)
Field joint coating type	select	HSS

Constant	f_i	=	0,009	-
Constant	Df	=	0,0006	-
Mean coating break down	f_{cm}	=	0,018	-
Final coating break down	f_{cf}	=	0,027	-

Current output:

Protective potential	E_c^0	=	-0,8	V
Closed circuit potential	E_a^0	=	-1	V
Enviromental resistivity	r	=	1,5	Wm

Anode:

Type		=	Al	
Bracelet		=	2	x half shell
Internal diameter		=	278,7	mm
Maximum thickness		=	38	mm
Initial anode diameter	D_{ani}	=	354,7	mm
Initial anode outside surface	A_{ani}	=	0,36	m^2
Final anode outside surface	A_{anf}	=	0,30	m^2
Anode length	L_{an}	=	323	mm
Initial net anode weight (half bracelet)	m_a	=	16,5	kg
Initial anode resistance	R_{ai}	=	0,79	W
Final anode resistance	R_{af}	=	0,87	W
Final individual anode current output	I_{af}	=	0,231	A
Distance between anodes		=	219,6	
Joint length		=	12,2	
Number of joints / anode		=	18,0	

Discretization no.	Discretised Length L_s [m]	Anode Temperature T_s [°C]	Total Area line pipe A_{c_LP} [m²]	Design mean current density i_{cm} [A/m²]	Mean current demand I_{cm_LP} [A]	Final current demand I_{cf_LP} [A]	Electro-chemical capacity e [Ah/kg]	Required total net anode mass m [kg]	Required number of anodes n [#]	Distance between anodes [m]	Total mass available M_a [kg]	Check 1: $m < M_a$	Available total end-of-life current output I_{af} (tot) [A]	Check 2: I_{af} (tot)≥ I_{cf}
1	219,6	60,0	188,41	0,055	0,187	0,280	800	77	**5,0**	43,92	82	**OK**	0,231	**OK**
2	219,6	42,4	188,41	0,037	0,127	0,190	1211	34	**3,0**	73,20	49	**OK**	0,231	**OK**
3	219,6	36,8	188,41	0,032	0,108	0,162	1340	26	**2,0**	109,80	33	**OK**	0,231	**OK**
4	219,6	32,3	188,41	0,027	0,093	0,139	1447	21	**2,0**	109,80	33	**OK**	0,231	**OK**
5	219,6	28,4	188,41	0,023	0,080	0,119	1500	17	**2,0**	109,80	33	**OK**	0,231	**OK**
6	219,6	25,2	188,41	0,020	0,069	0,103	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
7	219,6	22,6	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
8	219,6	20,4	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
9	219,6	18,5	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
10	219,6	17,0	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
11	219,6	15,8	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
12	219,6	14,6	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
13	219,6	13,7	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
14	219,6	12,9	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
15	219,6	12,2	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
16	219,6	11,7	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
17	219,6	11,2	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
18	219,6	10,8	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
19	219,6	10,4	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
20	219,6	10,2	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**

Discretization no.	Discretised Length L_s [m]	Anode Temperature T_s [°C]	Total Area line pipe A_{c_LP} [m²]	Design mean current density i_{cm} [A/m²]	Mean current demand I_{cm_LP} [A]	Final current demand I_{cf_LP} [A]	Electro-chemical capacity e [Ah/kg]	Required total net anode mass m [kg]	Required number of anodes n [#]	Distance between anodes [m]	Total mass available M_a [kg]	Check 1: $m < M_a$	Available total end-of-life current output I_{af} (tot) [A]	Check 2: I_{af} (tot)≥ I_{cf}
21	219,6	10,0	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
22	219,6	9,8	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
23	219,6	9,6	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
24	219,6	9,4	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
25	219,6	9,2	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
26	219,6	9,0	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
27	219,6	8,8	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
28	219,6	8,7	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
29	219,6	8,6	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
30	219,6	8,5	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
31	219,6	8,5	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
32	219,6	8,4	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
33	219,6	8,3	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
34	219,6	8,3	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
35	219,6	8,2	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
36	219,6	8,2	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
37	219,6	8,1	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
38	219,6	8,1	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
39	219,6	8,1	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
40	219,6	8,0	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**

Discretization no.	Discretised Length L_s [m]	Anode Temperature T_s [°C]	Total Area line pipe A_{c_LP} [m²]	Design mean current density i_{cm} [A/m²]	Mean current demand I_{cm_LP} [A]	Final current demand I_{cf_LP} [A]	Electro-chemical capacity e [Ah/kg]	Required total net anode mass m [kg]	Required number of anodes n [#]	Distance between anodes [m]	Total mass available M_a [kg]	Check 1: m < M_a	Available total end-of-life current output I_{af} (tot) [A]	Check 2: I_{af} (tot)≥ I_{cf}
41	219,6	8,0	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
42	219,6	8,0	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
43	219,6	8,0	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
44	219,6	8,0	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
45	219,6	7,9	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
46	219,6	7,9	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
47	219,6	7,9	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
48	219,6	7,9	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
49	219,6	7,9	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
50	219,6	7,9	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
51	219,6	7,9	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
52	219,6	7,8	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
53	219,6	7,8	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
54	219,6	7,8	188,41	0,020	0,068	0,102	1500	15	**1,0**	219,60	16	**OK**	0,231	**OK**
55	114,6	7,8	98,32	0,020	0,035	0,053	1500	8	**1,0**	114,60	16	**OK**	0,231	**OK**
Totals	11973,0							*total*	**64**					
joints	981,4								*1055,1*	*[kg]*				
									912,2	*[kg]*				

E.2 Bracelet type anode datasheet

Aluminum
Bracelet Anodes

Tapered Bracelets

Bracelet I.D.		TYPE *	THICKNESS		LENGTH		GAP		NET WT.		GROSS WT.	
in	mm		in	mm	in	mm	in	mm	lbs	kg	lbs	kg
2 3/8	60	T	1 1/4	32	12	305	1	25	11	5.0	13	5.9
3 1/2	89	T	1 1/4	32	12	305	1	25	15	6.8	17	7.7
4 1/2	114	T	1 1/2	38	12	305	1 1/4	32	23	10.4	25	11.3
4 1/2	114	T	1 1/2	38	19 1/4	489	1 1/4	32	46	20.9	50	22.7
5 9/16	141	T	1 1/2	38	15 5/8	397	1 1/4	32	37	16.8	40	18.1
6 5/8	168	T	1 1/2	38	11 1/4	286	1 1/2	38	32	14.5	36	16.3
6 5/8	168	TB2	1 1/2	38	13 1/2	343	3/4	19	32	14.5	36	16.3
6 5/8	168	T	1 1/2	38	13 5/8	346	1 1/2	38	36	16.3	40	18.1
6 5/8	168	T	1 1/2	38	18	457	1 1/4	32	60	27.2	64	29.0
6 5/8	168	T	1 3/4	44	21 1/4	540	1 1/2	38	74	33.6	78	35.4
6 5/8	168	ST	1 3/4	44	21 3/4	553	1 1/2	38	79	35.8	83	37.7
7 3/8	187	TB2	2 1/4	57	9 1/2	241	1	25	44	20.0	46	20.9
8 5/8	219	T	1 1/2	38	11 1/4	286	1 1/2	38	39	17.7	44	20.0
8 5/8	219	T	1 1/2	38	14 1/3	364	1 1/2	38	50	22.7	55	25.0
8 5/8	219	T	1 1/2	38	19.8	503	1 1/2	38	82	37.2	87	39.5
8 5/8	219	TB1	2 1/4	57	26 5/8	676	–	–	82	37.2	87	39.5
8 5/8	219	T	2 1/2	64	16	406	1 1/2	38	97	44.0	101	45.8
9 3/8	238	ST w/sockets	1 1/2	38	13 1/2	343	3	76	71	32.2	75	34.0
9 1/2	241	TB2	2 1/2	64	10 1/2	267	2	51	65	29.5	67	30.4
10 3/4	273	T	1 1/2	38	12.7	323	2	51	50	22.7	57	25.9
10 3/4	273	T	1 1/2	38	17 3/4	451	2	51	76	34.5	81	36.7
10 3/4	273	T	1 3/8	35	18 3/4	476	1 1/2	38	81	36.7	86	39.0
10 3/4	273	T	1 3/4	44	22	559	2	51	118	53.5	123	55.8
10 3/4	273	ST	1 3/4	44	22 1/4	565	2	51	124	56.3	131	59.4
10 3/4	273	TB1	3 1/4	83	24 1/2	622	–	–	131	59.4	145	65.8
10 3/4	273	ST	1 3/4	44	40	1016	2 1/2	64	227	103.0	237	107.5
12 3/4	324	T	1 1/2	38	14 3/4	375	2	51	74	33.6	84	38.1
12 3/4	324	T	1 1/2	38	16 3/4	425	1 1/2	38	94	42.64	100	45.4
12 3/4	324	ST	1 1/2	38	21.2	539	2 1/4	57	119	54.0	131	59.4
12 3/4	324	T w/sockets	1 1/2	38	23	584	4	102	125	56.7	131	59.4
12 3/4	324	T	2	51	19 5/8	498	2	51	149	67.6	162	73.5
12 3/4	324	ST1	1 3/8	35	31 1/2	800	2	51	165	74.8	177	80.3
13 9/16	345	T w/sockets	1 1/2	38	14	356	4	102	69	31.3	75	34.0
14	356	ST	1 1/2	38	21.1	536	2 1/4	57	131	59.4	144	65.3
14	356	ST	1 3/4	44	21 3/4	553	2	51	154	69.9	167	75.8
16	406	ST	1 3/4	44	20	508	2 1/4	57	169	76.7	184	83.5
16	406	ST1	1 1/2	38	32	813	2	51	210	95.3	225	102.0
16	406	ST	2	51	23	584	2 1/2	64	211	95.7	226	102.5
32	813	T	2	51	15 1/2	394	3	76	234	516	261	575
36	914	T	2 3/4	70	16 7/8	429	3	76	425	937	460	1014
40	1016	T	2	51	15 3/8	390	3	76	291	642	326	719

* T=Tapered
TB1=Tapered-Bolt-On (1 half only)
TB2=Tapered-Bolt-On
ST-Semi-Tapered
ST1=Semi-Tapered (One End Only)

Nominal weights and dimensions

REV 02/03