N05-A Pipeline design

Basic Design Report

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Project
N05-A Pipeline Design

Document
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1. Introduction

1.1. Project Introduction

ONEDyas plans to develop a successfully drilled well in block N05-A of the North Sea Dutch Continental Shelf. More wells will be drilled at this location through the same jacket. It is planned to develop the wells by installing a platform and a gas export pipeline with a subsea connection to the NGT pipeline's existing side tap connection @KP141.4. The approximate length of the pipeline is 14.6 km.

In addition, a power cable will be installed from the Riffgat Windpark to the N05-A platform.

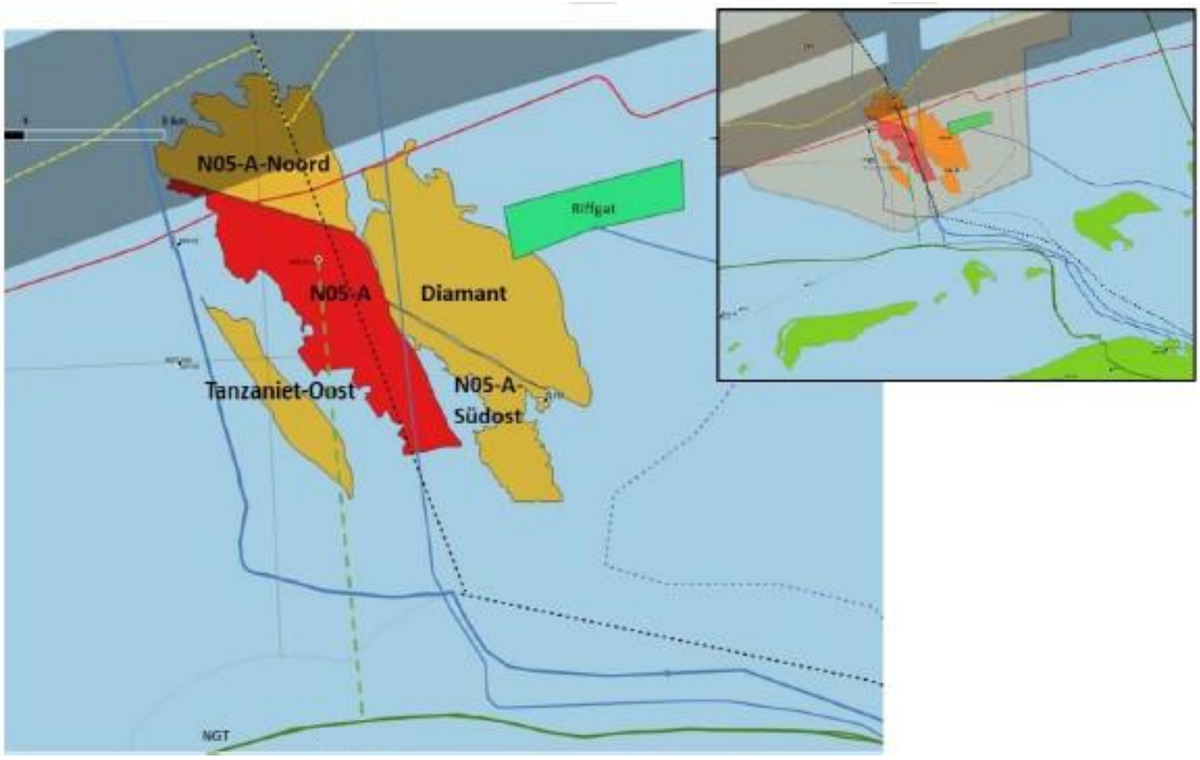


Figure 1, N05A Field layout

1.2. Purpose and Scope Document

The Basic Design Report documents the results of the calculations for the flowline, including:

- Wall Thickness analysis
- On-Bottom Stability analysis
- Buckling & Collapse analysis
- Static & Dynamic Free Span analysis
- Bottom roughness analysis
- Upheaval buckling 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

WD = Water Depth

1.5. References

1.5.1. 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.” June 2017.

[4] DNV RP-F107. “Risk Assessment of Pipeline Protection.” May 2017.

[5] DNV-RP-F109. “On-Bottom Stability Design of Submarine Pipelines.” May 2017

[6] DNV-RP-F110. “Global Buckling of Submarine Pipelines” April 2018.

[7] DNV-RP-C203. “Fatigue Design of Offshore Steel Structures.” April 2016.

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

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

[10] ASME Boiler and Pressure Vessel Code. Section VIII Rules for Construction of Pressure vessels. Division 1. July 2013.

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

[12] DNVGL-RP-F114 – “Pipe-soil interaction for submarine pipelines”, May 2017

1.5.2. Company Engineering Standards and Specifications

1.5.3. Project Reference Documents

[i] N05A-7-10-0-70028-01-02 – “Basis of Design Flowline”

[ii] N05A-7-10-0-70031-01-01 – “Route Selection Report”

[iii] N05A-7-51-0-72510-01-04 – “Overall field layout drawing”

[iv] N05A-7-50-0-72019-01-02 – Approach drawing @N05A

[v] N05A-7-10-0-70032-01-02 – “Approach drawing @NGT

[vi] N05A-7-10-0-70027-01-03 – “Flow Assurance Design Report”

[vii] N05A-7-10-0-70036-01-01 – “Flow Assurance Design report - Transient Analysis”

[viii] N05A-7-10-0-70035-01-01 – “On Bottom Stability Analysis Design Report”

[ix] Metocean Criteria for the N05A Platform – 181892_1_R2

[x] Metocean criteria for the N05A Platform Side Tap – 191146_1_R2

[xi] N5A VC-C-7 S-3 0300m CID

[xii] N5A VC-P-3 S-2 0405m CID

[xiii] N5A VC-P-8 S-4 0240m CID

[xiv] No5A-7-10-0-70030-01-02 Risk assessment dropped object analysis

[xv] 19018-10-PRE-01001-02-02 N05-A Progress meeting + Minutes of meeting, 2019-11-07

1.6. Holds

2. Summary

This document reports on the basic design stage of the flowline from the N05-A platform to the tie-in with the NGT pipeline. This includes:

- Wall Thickness analysis
- On-Bottom Stability analysis
- Buckling & Collapse analysis
- Static & Dynamic Free Span analysis
- Bottom roughness analysis
- Upheaval buckling analysis

The wall thickness analysis showed that a wall thickness of approximately 15mm would be required. It was chosen to select a wall thickness of 20.62 mm. The extra steel weight will assist the stability of the pipeline, which is further documented in a separate report (ref. [viii]).

The maximum allowable spans following from buckling & collapse and static and dynamic span analyses are determined for three depths: 8, 17, and 26 m (LAT), which corresponds to the water depths at the end, approximate middle, and start of the pipeline, respectively.

Criterion	8 m	17 m	26 m
B&C – bending and external pressure – Maximum span	62.6m (install/hydrotest) 76.7m (operation)	59.2m (install/hydrotest) 53.3m (operation)	56.0m (install/hydrotest) 43.8m (operation)
Static free span	66.3m (install/hydrotest) 91.3m (operation)	63.1m (install/hydrotest) 61.4m (operation)	60.1m (install/hydrotest) 52.1m (operation)
Dynamic free span: in-line VIV	21.9m (install/hydrotest) 20.9m (operation)	22.9m (install/hydrotest) 21.6m (operation)	25.2m (install/hydrotest) 23.7m (operation)
Dynamic free span: cross-flow VIV	36.0m (install/hydrotest) 35.3m (operation)	33..0m (install/hydrotest) 30.8m (operation)	37.2m (install/hydrotest) 30.7m (operation)

The bottom roughness analysis showed that the as-surveyed seabed will result in 1 span that is of unacceptable length during the installation phase. This span (27m) is present at KP0.4 at 26 m of water depth (section 9.3). The span criterion is based on in-line VIV, which could be mitigated if the pipeline dynamic response is investigated in the detail design phase.

Finally, an analytical upheaval buckling analysis was performed to determine a relation between the sand cover, imperfection heights and vulnerability to buckling under operational conditions (section 8.1).

3. Design Parameters

This chapter describes the design data to be considered for the pipeline (incl. spool pieces near the riser and the hot tap) from the new N05A-Platform to the NGT pipeline.

3.1. Pipe Data

The basic line pipe design and spool piece data to be considered in the analysis for the export gas line are presented in Table 3-1. Steel material properties considered in the design are presented in Table 3-2.

Property	
Product transported	Natural gas (dry)
Design life (years)	25
Approx. length (km)	14.6
Material grade	L360 NB
Manufacturing process	HFIW
Pipe outside diameter (“)	20”
Pipe outside diameter (mm)	508
Pipe internal diameter	466.76
Wall thickness (mm)	20.62 (Sch60)
Wall thickness tolerance (%)	7.3
Wall thickness tolerance (mm)	+/- 1.5mm
Internal corrosion allowance (mm)	3
Anti-corrosion coating	3LPP
Anti-corrosion coating thickness (mm)	3
Anti-corrosion coating density (kg/m^3)	930
(Concrete) weight coating thickness (mm)	N.A
concrete weight coating density (kg/m^3)	3300
Minimum hot bend radius (mm)	2540 (5D)

Table 3-1 Pipeline data

Property	
Material	L360NB
Density (kg/m3)	7850 kg/m^3
Specified Minimum Yield Strength at 20°C (MPa)	360
Specified Minimum Yield Strength at 50°C (MPa)	360
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 3-2 Material properties

3.2. Process Conditions

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

Property	Export gas line
Design pressure	111.1 bar(g)
Operating pressures	95 bar(g)
Design temperature (min / max)	-20 °C / 50 °C
Operating temperature (min / max)	1 / 43 °C
Ambient (air / surface) temperature	-6.8°C / +24.2 °C
Content density (arrival, nominal operation)	88.7 / 96.1 kg/m³
Design flowrate (min/max)	0.14 / 6.0 MMNm3/d

Table 3-3 Process design parameters

Figure 3-1 shows the operational thermal profile along the pipeline, ref. [vii] .

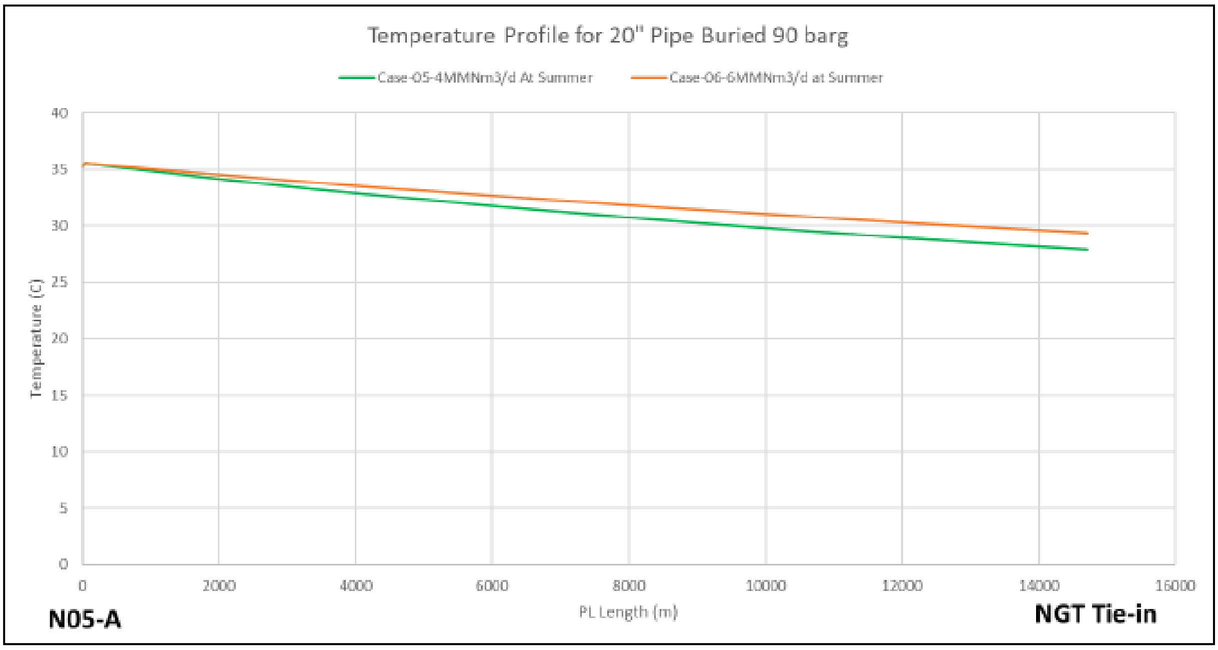


Figure 3-1 Operational thermal profile, nominal operation in summer

3.3. Coating Material Properties

Typical material properties of the coating are given in Table 3-4.

Property	Value
Anti-corrosion material type	3LPP
Anti-corrosion coating density	930 kg/m³
Anti-corrosion coating thermal conductivity	0.22 W/m°C
Anti-corrosion coating specific heat capacity	2000 J/kg°C

Table 3-4 Steel pipe coating material properties

3.4. Flange Properties

Table 3-5 presents the flange classes and main characteristics. The flange loads will be checked by using the ASME BPVC [10] flange integrity check. Note that table 3-5 is applicable to all flanges on the flowline and spool pieces.

Property	Export gas line
Flange rating	ANSI/ASME Class 1500
Flange type	RTJ Swivel / Weld Neck
Weld end thickness	20.62mm

Table 3-5 Flange properties

3.5. Environmental Data

For the design of the pipeline, environmental data has been taken from Ref. [ix] and [x]. Where Ref [ix] contains the metocean data for the platform (water depth 26 m); Ref [x] contains the Metocean data for the NGT tie-in (water depth 8 m) target box. Tables 3-6 to 3-11 present the relevant metocean data for the 1 and 100 year design conditions for the applicable locations.

The shallow water depths encountered along the pipeline route pose problems in determining the hydrodynamics loads encountered by the pipeline. Enersea has developed a calculation method based on Stokes 5th order wave theory, however in shallow waters this method is not applicable. The metocean reports [ix, x] provide a wave orbital velocity at 1 m above the sea bed, denoted as U_{1m}. For the water depth of 26 m, the Stokes theorem is at the limit of applicability and produces wave velocity approximately 10% higher than provided in the metocean report for this depth. To remain conservative, the higher velocity has been used for the location of 26 m water depth.

In order to establish environmental conditions at an intermediate pipeline location with a water depth of 17m, current and wave particle velocities have been averaged. This approach has been agreed with One-Dyas [xv].

Property	1-year return period	100-year return period
Positive surge (m) @26m	1.58	3.04
Negative surge (m)	-1.02	-1.79
LAT with respect to MSL (m)	-1.41	
HAT with respect to MSL (m)	1.31	

Table 3-6 Near platform extreme water level data [ref. II]

Return Period Depth Level	Extreme Cs [m/s] Direction [towards]								OMNI
	N	NE	E	SE	S	SW	W	NW	
1-year									
Near-surface	0.36	0.94	0.98	0.70	0.42	0.77	0.98	0.59	0.98
Mid-Depth	0.40	0.89	0.90	0.53	0.27	0.62	0.90	0.51	0.90
Near-bed	0.38	0.74	0.74	0.42	0.25	0.56	0.74	0.43	0.74
100-years									
Near-surface	0.46	1.21	1.27	0.91	0.55	1.00	1.27	0.76	1.27
Mid-Depth	0.51	1.15	1.16	0.68	0.35	0.79	1.16	0.66	1.16
Near-bed	0.49	0.95	0.96	0.55	0.32	0.72	0.96	0.55	0.96

Table 3-7- Near platform design current data [ref. II]

Return Period Direction [from]	Hs [m]	Tz [s]	Tp [s]	Cmax [m]	Hmax [m]	THmax [s]	U_{1m} [m/s]
1-year							
North	5.3	9.2	11.7	5.9	9.3	9.5	1.67
North-east	3.8	6.8	8.3	4.3	6.7	8.5	1.04
East	2.6	5.2	6.6	3.0	4.7	7.5	0.55
South-east	2.1	4.6	5.2	2.3	3.6	6.9	0.34
South	2.4	4.7	5.2	2.8	4.3	7.3	0.48
South-west	3.2	5.6	6.2	3.6	5.6	8.0	0.78
West	4.7	8.0	10.5	5.3	8.3	9.1	1.43
North-west	6.5	9.9	12.4	7.3	11.4	10.1	2.19
100-years							
North	8.1	11.5	14.3	9.1	13.8	10.8	2.73
North-east	5.9	8.1	10.4	6.6	10.0	9.7	1.84
East	4.0	5.9	8.2	4.5	6.9	8.6	1.07
South-east	3.1	4.9	6.0	3.5	5.4	7.9	0.71
South	3.7	5.0	6.0	4.2	6.4	8.4	0.95
South-west	4.9	6.4	7.3	5.5	8.3	9.1	1.43
West	7.2	9.8	12.9	8.1	12.3	10.4	2.40
North-west	9.9	12.3	14.9	11.1	16.9	11.5	3.20

Table 3-8 Near platform design wave data [ref. II]

Property	1-year return period	100-year return period
Positive surge (m) @8m	1.48	2.72
Negative surge (m)	-0.90	-1.26
LAT with respect to MSL (m)	-1.89	
HAT with respect to MSL (m)	1.61	

Table 3-9 Near tie-in extreme water level data [ref. III]

Return Period Depth Level	Extreme Cs [m/s] Direction [towards]								Omni
	N	NE	E	SE	S	SW	W	NW	
1-year									
Surface	0.31	0.52	1.04	0.51	0.27	0.50	1.04	0.59	1.04
Mid-depth	0.30	0.50	1.01	0.44	0.25	0.43	1.00	0.55	1.01
Near-bed	0.26	0.45	0.89	0.23	0.10	0.19	0.61	0.39	0.89
100-years									
Surface	0.37	0.63	1.25	0.62	0.32	0.60	1.25	0.71	1.25
Mid-depth	0.36	0.60	1.21	0.53	0.31	0.52	1.20	0.66	1.21
Near-bed	0.33	0.57	1.12	0.29	0.13	0.23	0.77	0.49	1.12

Table 3-10 Near side tao tie-in design current data [ref. III]

Return Period Direction [from]	Hs [m]	Tz [s]	Tp [s]	Cmax [m]	Hmax [m]	THmax [s]	U_{1m} [m/s]
1-year							
North	3.6	6.2	10.3	3.3	4.8	7.5	1.2
North-east	2.2	4.9	7.7	2.0	2.9	6.5	0.6
East	1.6	3.9	5.0	1.5	2.2	5.9	0.4
South-east	1.5	3.6	3.7	1.4	2.0	5.8	0.3
South	1.4	3.5	3.9	1.3	1.9	5.7	0.3
South-west	2.0	4.1	4.5	1.9	2.7	6.3	0.5
West	3.0	5.7	10.2	2.8	4.1	7.2	0.9
North-west	3.9	6.4	12.1	3.6	5.2	7.7	1.3
100-years							
North	3.9	6.4	10.6	4.2	5.7	7.9	1.5
North-east	2.4	5.1	7.9	2.6	3.5	6.8	0.8
East	1.7	4.1	5.2	1.9	2.6	6.2	0.5
South-east	1.6	3.7	3.8	1.8	2.4	6.1	0.4
South	1.6	3.7	4.1	1.7	2.3	6.0	0.4
South-west	2.2	4.3	4.6	2.4	3.2	6.7	0.7
West	3.3	6.0	10.7	3.6	4.9	7.5	1.2
North-west	4.2	6.6	12.6	4.5	6.2	8.1	1.6

Table 3-11 Near tie-in design wave data [ref. III]

3.6. Marine Growth

The following marine growth has been assumed, in accordance with NEN 3656 [1]

From	To	Thickness	Density
+2m LAT	Seabed	50mm	1300 kg/m3

Table 3-12 Assumed marine growth properties

3.7. Geotechnical Data

Three lab result reports , Refs [xi] through [xiii], present properties of soil samples taken. These classify the soil as fine to medium sand. The soil properties are listed in Table 3-13, data has been taken from the lab reports and recommended values as per NEN3656 table H.1 ref[1] based on the soil description as presented in. A SBP data example of the north end of the proposed route is presented in figure 3-14.

Soil type	Applicable area	Submerged Unit Weight (kN/m³)	Angle of internal friction (°)
Medium sand (measured)		10.2-10.5	32.5-34.9
Medium sand	Pipe on surface	10	32.5
	Trench backfill	8.5	28
Rock dump	Crossing / Tie-in	10	40

Table 3-13 Assumed soil geotechnical properties

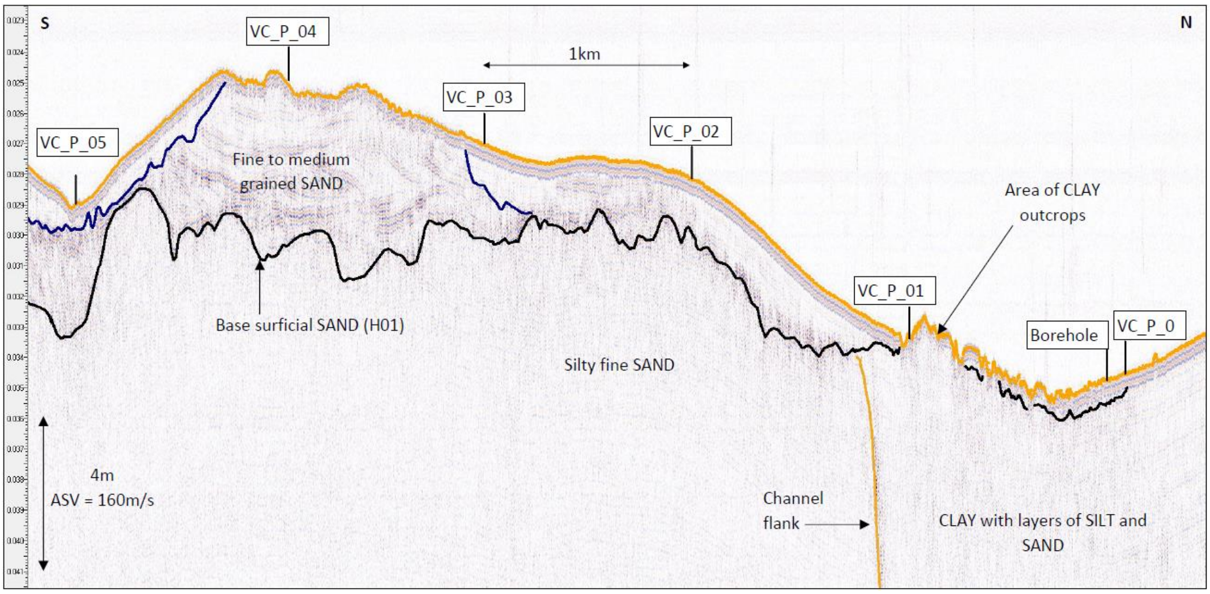


Figure 3-2 Soil profile from KP 0.0 to KP 6.0

4. Pipeline Route Data

This chapter deals with the pipeline route data describing the starting and end point of the pipeline, the used coordinate system, pipeline route coordinates and key facilities as well as the route bathymetry and contacts detected along the pipeline route. Based on this info the most optimal pipeline routing has been selected (ref. [ii].

4.1. General

The new pipeline to be installed originates at the new N05-A Platform and terminates at the NGT platform via a dedicated tie-in connection. The pipeline length is approx. 14.6 km.

An installation of the pipeline on top of the seabed has been indicated as an opportunity. The final cover height, or required concrete coating thickness will be determined based on the results of a risk assessment study [xiv], the on-bottom stability analysis [viii] and the upheaval buckling analysis.

Two pipeline/cable crossings are foreseen along the route. An overview of the field lay out is given in Figure 4-1.

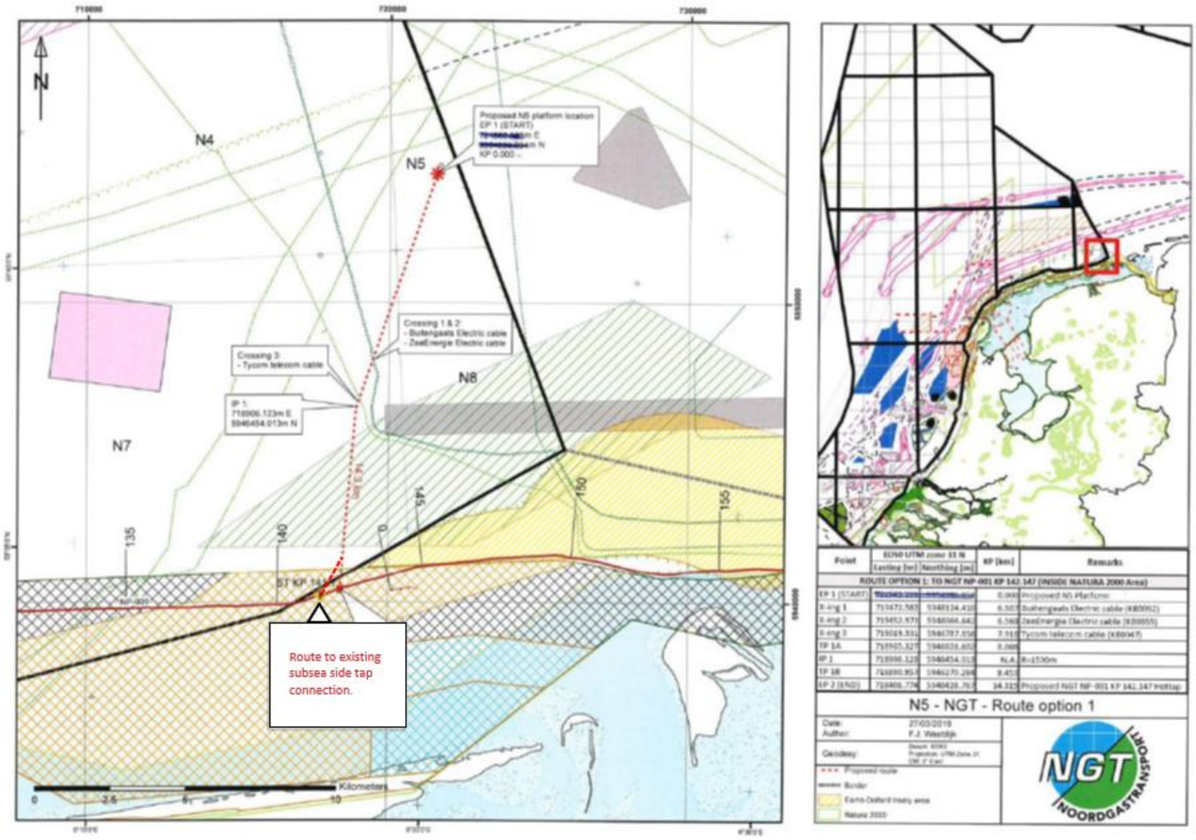


Figure 4-1 Overview N05A platform to the existing side tap tie-in location (left)

4.2. Coordinate System

The parameters of the geodetic system to be used for horizontal positions are listed in Table 4-1.

Item	Value
Datum	European Datum 1950 (ED50)
Projection	ED50 / UTM zone 31 N
Ellipsoid name	International 1924
Semi major axis	6 378 388 m
Inverse flattening	297.000
Central Meridian	03°00"00' E
Latitude of Origin	00°00"00' N
False Northing	0 mN
False Easting	500 000 mE
Scale Factor	0.9996

Table 4-1: Geodetic parameters

The vertical position is given relative to the Lowest Astronomical Tide (LAT).

4.3. Key Facility Coordinates

The following platform and tie in locations have been derived from Ref. [ii] and are presented in Table 4-2.

Item	Northing (m)	Easting (m)
N05A Platform target box	5 953 858	721 896
NGT target box	5 940 213	718 687
NGT hot tap location KP142.1	5 940 197	718 698
Water depth at N05A Platform	25.3m LAT	
Water depth at NGT hot tap	9.8 m LAT	

Table 4-2 Key Facility coordinates

4.4. Bathymetry

Figure 4-3 shows the bathymetry along the surveyed flowline route. The water depths recorded during survey along the proposed N05-A platform and the NGT pipeline side tap location ranges between 9.8 m LAT and 25.3m LAT.

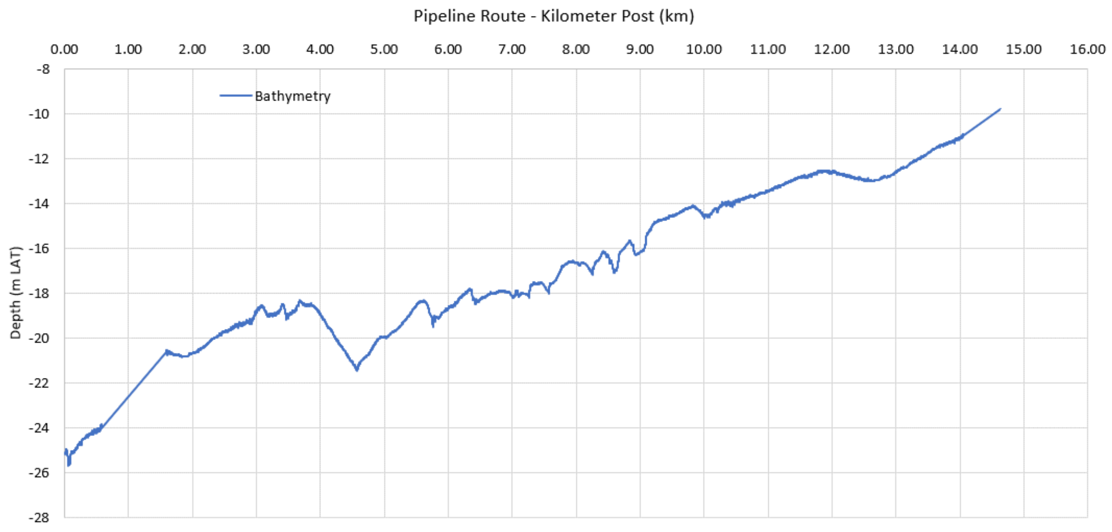


Figure 4-3 Seabed profile along pipeline route from N05-A Platform to NGT side tap connection

4.5. Side Scan Sonar Contacts & Magnetometer Anomalies

Ref. [5] describes the seafloor sediments across the N05-A to the proposed NGT hottap location survey area to consist of a top layer of fine to coarse sand, with occasional areas of coarse sand and clay with gravel and shell fragments. Photographs taken along the proposed route show the presence of small ripples covering the majority of the seabed within the survey corridor area.

Numerous boulders and items of debris are observed in the survey area. Most of the boulders occur in the north of the survey area and coincide with areas of clay exposure.

4.5.1. Magnetometer Anomalies

A total of 241 magnetic anomalies (appendix A) were picked within the surveyed N05-A platform to the 36" NGT Tie-in and N05-A platform to Riffgat Tie-in route corridor. Most of these anomalies can be attributed to unknown identified seabed features the following seabed infrastructures are known, one (1) pipeline and four (4) cables. However, one (1) unknown linear feature.

The following existing pipelines and cable are detected:

- 36" Pipeline from L10-AR to Uithuizen
- Tycom Telecom cable
- Buitengaats Power cable
- Zeeenergie Power cable
- Norned Power cable

4.5.2. Side Scan Sonar Contacts

Eight-Hundred-Thirty (830) side scan sonar contacts were observed within the route survey. Most of the contacts are boulders located around the N05-A platform and stretching to the east side to Riffgat, besides the bolders the following contacts are found, twenty-six (26) debris items, two (2) wrecks.

4.6. Pipeline and Cable Crossings

The following crossings along the pipeline route are envisaged:

Infrastructure Name	KP	Northing (m)	Easting (m)
Buitengaats Electric cable	5.956	5.948.587	719.395
ZeeEnergie Electric cable	6.036	5.948.510	719.373
Tycom Telecom Cable Hunmanby GAP - Eemshaven	7.629	5.946.979	718.931

*) The N05A Pipeline will be connected to the NGT Pipeline with a side tap. This side tap is not part of the scope of this design report.

4.7. Approach

Near the platform a T-piece will be installed including 2 ball valves for the purpose of a future pipeline connection. At the NGT tie-in location 2 ball valves and a check valve will be placed for tie-in purposes. Figures 4-4 and 4-5 present an overview of respectively the platform and the tie-in location.

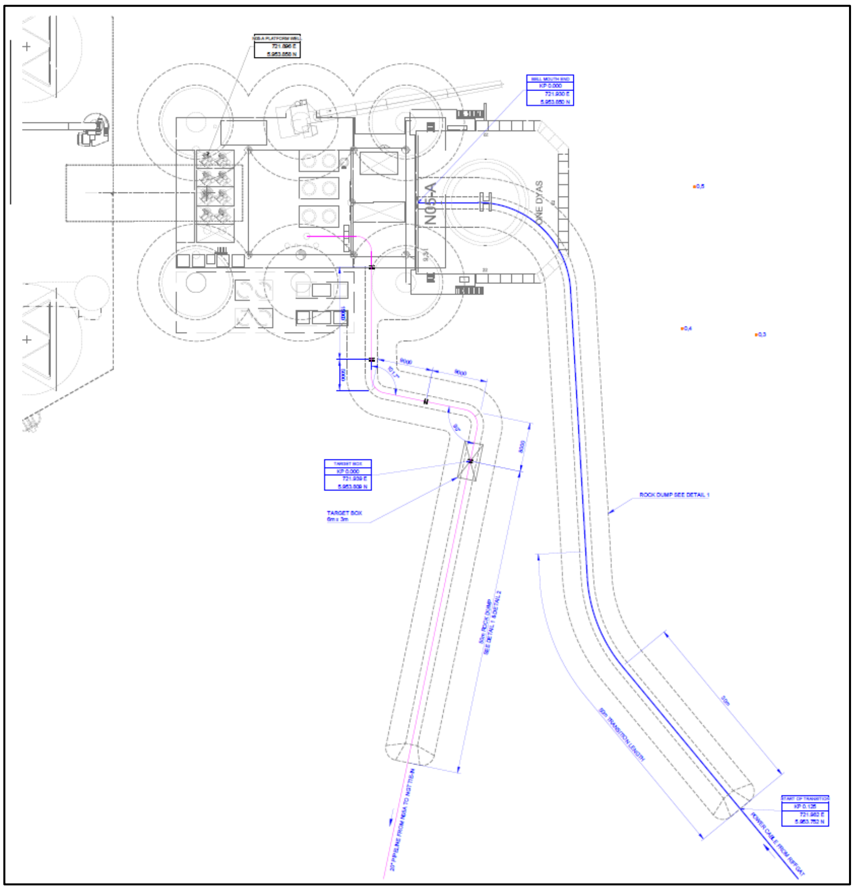


Figure 4-4 approach layout near the platform

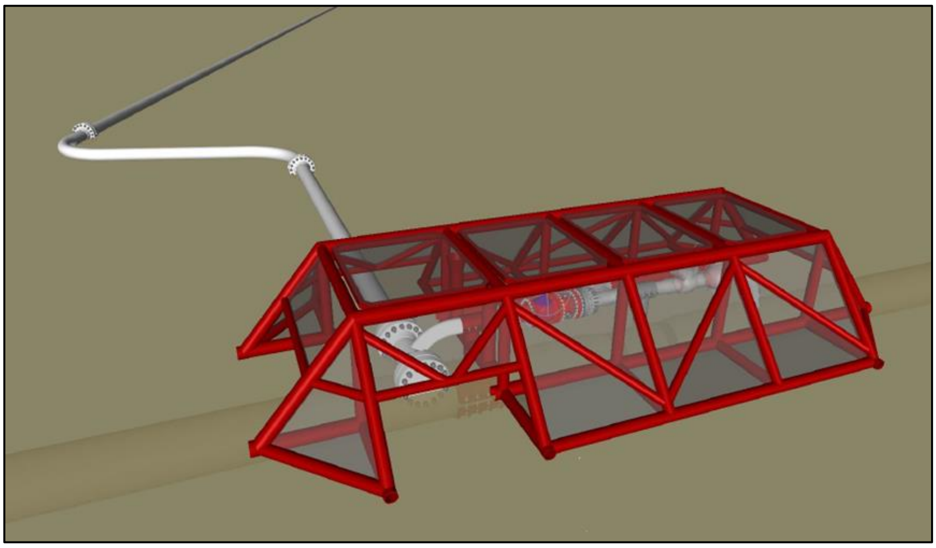


Figure 4-5 approach layout near the NGT side tap tie-in

5. Stress Criteria & Load Factors

5.1. Stress Criteria

Stresses in the flowline will be assessed according NEN 3656 (Ref. [1])
The analysis will account for the load history of the pipe over the design life by considering the following three load cases:

- Installation
- Hydrotest
- Operational

Considering the design cases listed above the following design loads will be considered when performing the stress analysis, see Table 5-1. The hydrodynamic loads for pipeline stability and maximum span are included via analytical calculations, see chapters 6 and 7.

Load	Installation	Hydrotest	Operation
Pressure	N/A	Hydrotest Pressure	Operational Pressure
Temperature	Seawater Temperature	Seawater Temperature	Operational Temperature
Internal Fluid	Seawater	Seawater	Product Filled
Wall Thickness	Nominal	Nominal	Nominal / Fully corroded
Hydrodynamic Loads	1-year wave + 1-year current	1-year wave + 1-year current	100/10-year wave + 10/100-year current

Table 5-1 Design loads

Calculated equivalent stresses for the various design conditions will be checked against the allowable stress values, as per NEN3656 (Ref. [1]), see Table 5-2.

Case	Load Combination As Per NEN3656 Table 3.	Limit Stress	Allowable Equivalent Stress (L360NB)
Installation	LC1	$R_{e(\theta)} / \gamma_m$	327 MPa
Hydrotest	LC4	$0.85\ (R_e + R_{e(\theta)})/\ \gamma_m$	556 MPa
Operation (Nominal / Corroded)	LC4	$0.85\ (R_e + R_{e(\theta)})/\ \gamma_m$	556 MPa

Table 5-2 Applied stress limits

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).

5.2. Load Factors

All design loads applied will be factored as per the requirements of NEN 3656 (Ref. [1]), see Table 5-3.

Loads	Load factors for load combinations (a)								
Load combinations	LC 1	LC 2	LC 3	LC 4	LC 5	LC 6	LC 7a	LC 7b	LC 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	-	1.10	-	-	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	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 5-3 Load factors

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 7a: Incidental load (other than internal pressure)

LC 7b: Incidental load (meteorological)

LC 8: Dynamic loading

5.3. 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 5-4.

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 5-4 Overview hydrodynamic coefficients

Typically, the peak hydrodynamic load is experienced just after the peak wave particle velocity, due to the additional inertia contribution. As stated in Section 3.5, wave models are not used in the shallow water depths, but only the peak velocity from the metocean report. No information on the particle acceleration is provided, however. The contribution of the inertia term is typically <10% of the drag term at peak velocity. To be conservative, a 20% margin is added to the drag term.

6. Wall Thickness Analysis

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;

6.1. Pressure Containment

6.1.1. Design Condition

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:

S_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 straight pipe (torus effect).

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

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

6.1.2. Hydrostatic Testing

The hydrostatic testing of pipeline / riser systems 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 either $P_{t,max}$ or $P_{T,mill}$, the mill test pressure. Respectively, these are defined as:

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

$$P_{T,mill} = 0.9 \cdot \frac{2 \cdot R_e \cdot t_{nom}}{OD}$$

Where:

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

Where:

t_{nom}	=	nominal wall thickness (mm)
t_{min}	=	minimum wall thickness (mm)
CA	=	applicable corrosion Allowance (mm)
f_{tol}	=	fabrication tolerance (%)

6.1.3. Results

An overview of the results of the wall thickness calculations is given in Table 6-1.

Property	Inside 500 m	Outside 500 m
Minimum WT (mm)	11.50	10.55
Minimum WT inside bend (mm)	12.13	11.14
Minimum WT outside bend (mm)	10.97	10.07
Nominal (with corrosion allowance) minimum WT (mm)	14.50	13.55
Nominal WT inside bend (mm)	15.13	14.14
Nominal WT outside bend (mm)	13.97	13.07
Selected minimum WT	20.62	20.62
Hoop stress (MPa)	232	212
Hoop stress inside bend (MPa)	244	224
Hoop stress outside bend (MPa)	221	203
Allowable stress at design temperature (MPa)	327	327
Minimum hydrotest pressure (barg)	144	144
Maximum hydrotest pressure (barg)	281	281
Mill test pressure (barg)	263	263

Table 6-1 Overview wall thickness analysis results

Reference is made to Appendix A for the detailed calculations.

6.2. On-Bottom Stability

The aim of the stability analysis is to verify that the submerged weight of the pipeline ensures lateral stability against environmental loading.

Reference is made to report “N05A-7-10-0-70035-01 N05A On Bottom Stability Analysis Design Report” (ref. [viii]) for detailed OBS analyses.

From this report it can be seen that in order to provide absolute stability during the pipeline lifetime, in which the 100-year storm conditions are applied (non-buried pipeline), an excessively thick concrete weight coating would be required (>> 500 mm). Relaxation of the displacement criterium to allow up to 10D displacement would require a minimal concrete weight coating of over 130 mm. As the determined pipeline displacements are for a single storm only, it cannot be guaranteed that the pipeline will settle in a final position. Hence the pipeline can displace even further during a next storm, potentially causing (too) high stresses/strain.

This, in combination with shallow water depths and installation limitations, results in the recommendation to bury the pipeline.

A buried pipeline is exposed to 1-year return period conditions, but still absolute stability cannot be guaranteed. However viable designs are possible when 0.5D - 10D displacements are allowed. As the timespan between the flooded lay of the pipe and trenching thereof will be minimum, it is deemed acceptable that for a buried pipeline, no additional weight coating is applied.

6.3. Implosion

6.3.1. External Overpressure

The collapse pressure p_c causing implosion (radial instability) 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)
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	=	actual external pressure (N/mm^2)
δ_0	=	initial deformation (mm)
t	=	nominal wall thickness (mm)

$$D_g = \frac{1}{2}\cdot\{OD_{nom} - (OD_{nom} - 2\cdot t_{min})\}$$

The critical external pressure for plastic deformation is calculated from:

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

The critical external pressure 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

6.3.2. 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 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)

6.3.3. 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)

6.4. 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 5.

6.5. Local Buckling

In accordance with NEN 3656, if OD / t < 55, an assessment on local buckling can generally be omitted.

For this project it would mean that a local buckling check is required for a wall thickness of minimal 9.2 mm, which will be much smaller than the anticipated wall thickness. This will be checked during detailed design.

6.6. 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. The compressive force 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)

6.7. Results Buckling & Collapse

Appendix B contains the calculation sheet for the buckling and collapse calculations discussed in the previous sub-sections. The results are also summarized in Table 6-3 (8m WD), Table 6-4 (17m WD) and Table 6-5 (26m WD).

Property	Install (flooded	Hydrotest	Operation
Material	L360		
Temperature (deg. C)	15	15	65
Yield at temperature (N/mm2)	360	360	360
Pressure (barg)	2	144	111
Content density (kg/m3)	1025	1025	96
Storm surge (m)	-0.14		-0.78
Hmax (m)	5.2		6.2
Tass (s)	7.7		8.1
Current velocity @ 1m ASB (m/s)	0.89		1.12
Collapse – external pressure only			
Actual external pressure (MPa)	0.19		
Allowable external pressure (MPa)	16.0		
Check	OK		
Collapse – bending moment only			
Maximum allowable bending moment (kNm)	1256		
Collapse – external pressure & bending moment			
Maximum allowable bending moment (kNm)	1001		1001
Maximum span length collapse (m)	62.6	62.6	76.7
Progressive plastic collapse			
Actual strain (-)	0.0001	0.0001	0.0005
Allowable strain (-)	0.0033	0.0028	0.0030
Check	OK	OK	OK
Local buckling			
OD/t ratio	23.9		
Allowable ratio	55		
Check	OK		
Bar buckling			
Maximum span length (m)	93.1	- (No compressive force)	61.7

Table 6-3 Buckling & Collapse analysis - result summary – 8 m water depth

Property	Install (flooded	Hydrotest	Operation
Material	L360		
Temperature (deg. C)	15	15	65
Yield at temperature (N/mm2)	360	360	360
Pressure (barg)	2	144	111
Content density (kg/m3)	1025	1025	96
Storm surge (m)	-0.58		-1.29
Hmax (m)	8.3		11.55
Tass (s)	8.9		9.8
Current velocity @ 1m ASB (m/s)	0.82		1.04
Collapse – external pressure only			
Actual external pressure (MPa)	0.30		
Allowable external pressure (MPa)	16.0		
Check	OK		
Collapse – bending moment only			
Maximum allowable bending moment (kNm)	1256		
Collapse – external pressure & bending moment			
Maximum allowable bending moment (kNm)	1000		1000
Maximum span length collapse (m)	59.2	59.2	53.3
Progressive plastic collapse			
Actual strain (-)	0.0001	0.0001	0.0005
Allowable strain (-)	0.0033	0.0028	0.0030
Check	OK	OK	OK
Local buckling			
OD/t ratio	23.9		
Allowable ratio	55		
Check	OK		
Bar buckling			
Maximum span length (m)	93.1	- (No compres-sive force)	61.7

Table 6-4 Buckling & Collapse analysis - result summary – 17 m water depth

Property	Install (flooded	Hydrotest	Operation
Material	L360		
Temperature (deg. C)	15	15	65
Yield at temperature (N/mm2)	360	360	360
Pressure (barg)	2	144	111
Content density (kg/m3)	1025	1025	96
Storm surge (m)	-1.02		-1.79
Hmax (m)	11.4		16.9
Tass (s)	10.1		11.5
Current velocity @ 2m ASB (m/s)	0.74		0.96
Collapse – external pressure only			
Actual external pressure (MPa)	0.42		
Allowable external pressure (MPa)	16.0		
Check	OK		
Collapse – bending moment only			
Maximum allowable bending moment (kNm)	1256		
Collapse – external pressure & bending moment			
Maximum allowable bending moment (kNm)	999.4		999.4
Maximum span length collapse (m)	56.0	56.0	43.8
Progressive plastic collapse			
Actual strain (-)	0.0001	0.0001	0.0005
Allowable strain (-)	0.0033	0.0028	0.0030
Check	OK	OK	OK
Local buckling			
OD/t ratio	23.9		
Allowable ratio	55		
Check	OK		
Bar buckling			
Maximum span length (m)	93.1	- (No compres-sive force)	61.7

Table 6-5 Buckling & Collapse analysis - result summary – 26 m water depth

7. Free Span Analysis

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.

7.1. 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 5-3 (-)
γ_H	=	load factor as per Table 5-3 (-)

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

7.1.1. Load Cases

The maximum static span will be determined for the load cases, and considering the environmental load return periods, as detailed in Table 7-1:

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 7-1 Load Cases for Span Assessment

7.1.2. Results

Tables 7-2 thru 7-5 show the results for the maximum allowable static span lengths during installation, hydro-test and operational phase. The calculation can be found in Appendix C.

7.1.2.1. Flooded installation

Property	Unrestrained pipe		Restrained pipe	
	Tension	Compression	Tension	Compression
Hoop stress (MPa)	2.9	2.9	2.9	2.9
Max. longitudinal stress (MPa)	328.7	-325.8	328.7	-325.8
Longitudinal hoop stress (MPa)	1.2	1.2	0.9	0.9
Thermal expansion stress (MPa)	N/A	N/A	-26.8	-26.8
Max. allowable bending stress (MPa)	327.3	-327.1	327.3	-299.9
Max. allowable span (m) – 8 m WD	69.3	69.3	69.3	66.3
Max. allowable span (m) – 17 m WD	65.9	65.9	65.9	63.1
Max. allowable span (m) – 26 m WD	62.8	62.7	62.8	60.1

Table 7-2 Maximum span for flooded pipe

7.1.2.2. Hydrotest

Property	Unrestrained pipe		Restrained pipe	
	Tension	Compression	Tension	Compression
Hoop stress (MPa)	249.7	249.7	249.7	249.7
Max. longitudinal stress (MPa)	637.5	-387.8	637.5	-387.8
Longitudinal hoop stress (MPa)	85.8	85.8	74.9	74.9
Thermal expansion stress (MPa)	N/A	N/A	-29.5	-29.5
Max. allowable bending stress (MPa)	551.6	-473.6	556.4	-433.2
Max. allowable span (m) – 8 m WD	89.3	82.6	89.7	79.0
Max. allowable span (m) – 17 m WD	84.4	78.2	84.8	74.8
Max. allowable span (m) – 26 m WD	79.9	74.2	80.3	70.9

Table 7-3 Maximum span during hydrotest

7.1.2.3. Operation LC1

Property	Unrestrained pipe		Restrained pipe	
	Tension	Compression	Tension	Compression
Hoop stress (MPa)	191.8	191.8	191.8	191.8
Max. longitudinal stress (MPa)	626.9	-435.1	626.9	-435.1
Longitudinal hoop stress (MPa)	66.2	66.2	57.6	57.6
Thermal expansion stress (MPa)	N/A	N/A	-123.3	123.3
Max. allowable bending stress (MPa)	556.4	-501.2	556.4	-369.4
Max. allowable span (m) – 8 m WD	112.2	106.4	112.2	91.3
Max. allowable span (m) – 17 m WD	75.4	71.5	75.4	61.4
Max. allowable span (m) – 26 m WD	63.9	60.7	63.9	52.1

Table 7-4 Maximum span for Load Case 1

7.1.2.4. Operation LC2

Property	Unrestrained pipe		Restrained pipe	
	Tension	Compression	Tension	Compression
Hoop stress (MPa)	191.8	191.8	191.8	191.8
Max. longitudinal stress (MPa)	626.9	-435.1	626.9	-435.1
Longitudinal hoop stress (MPa)	66.2	66.2	57.6	57.6
Thermal expansion stress (MPa)	N/A	N/A	-123.3	123.3
Max. allowable bending stress (MPa)	556.4	-501.2	556.4	-369.4
Max. allowable span (m) – 8 m WD	112.4	106.5	112.4	91.5
Max. allowable span (m) – 17 m WD	84.3	80.0	84.3	68.7
Max. allowable span (m) – 26 m WD	73.6	70.0	73.6	60.0

Table 7-5 Maximum span for Load Case 2

7.2. Dynamic Span

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 $K_s \le 1.8$ and cross flow oscillations will occur if $K_s \le 16$.

7.2.1. In-line VIV

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

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*Twave. 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 0.5. In the domain 0.5< α<0.8, in-line VIV is described as ‘reduced’ and requires additional work in determining the response amplitude. This additional work is left for the detail design phase.

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

Where,

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

7.2.2. 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 7-1.

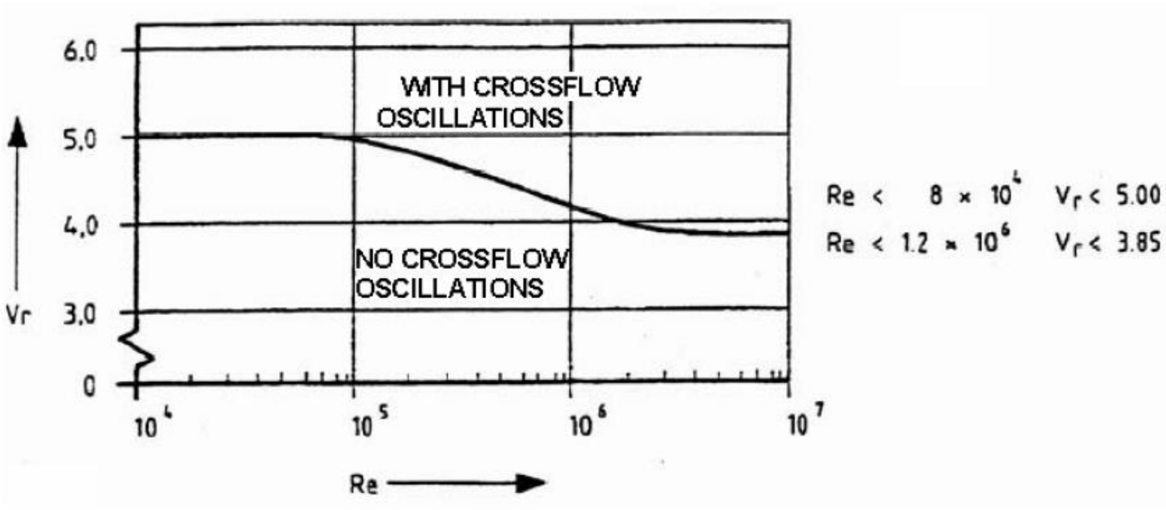


Figure 7-1 Reduced velocity for cross flow oscillations

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

Where,

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

7.2.3. Results

The results for the VIV analyses are presented in Tables 7-6 through 7-8. Reference is made to appendix C for more detailed calculations.

In-line VIV:

Property	Installation (flooded)	Hydrotest	Operation LC1	Operation LC2
8m WD - Wave hor. particle velocity (m/s)	1.3	1.3	1.6	1.5
8m WD - Current hor. particle velocity (m/s)	0.71	0.71	0.79	0.81
8m WD - Current velocity ratio (-)	0.35	0.35	0.35	0.37
17m WD - Wave hor. particle velocity (m/s)	1.33	1.33	2.08	1.76
17m WD - Current hor. particle velocity (m/s)	0.65	0.65	0.73	0.83
17m WD - Current velocity ratio (-)	0.33	0.33	0.26	0.32
26m WD - Wave hor. particle velocity (m/s)	1.35	1.35	2.56	2.01
26m WD - Current hor. particle velocity (m/s)	0.53	0.53	0.60	0.69
26m WD - Current velocity ratio (-)	0.28	0.28	0.19	0.26

Table 7-6 Current velocity ratio per load case

The current flow velocity ratio (α) is <0.5 for all load cases. Below this ratio, in-line VIV due to vortex shedding becomes negligible (DNV-RP-F105, Ref [3]). In the limit of $\alpha = 0.5$, the acceptable span is determined below:

Property	Installation (flooded)	Hydrotest	Operation LC1	Operation LC2
Effective mass (kg/m)	682.9	682.9	522.7	522.7
Stability parameter (-)	0.63	0.63	0.49	0.49
Reduced velocity limit (-)	1	1	1	1
Outer P/L diameter (mm)	514	514	514	514
8m WD				
Wave hor. particle velocity (m/s)	0.71	0.71	0.79	0.81
Current hor. particle velocity (m/s)	0.71	0.71	0.79	0.81
Current velocity ratio (-)	0.5	0.5	0.5	0.5
Span frequency (1/s)	2.75	2.75	3.09	3.46
Allowable span length (m)	21.9	21.9	22.1	20.9
17m WD				
Wave hor. particle velocity (m/s)	0.65	0.65	0.73	0.83
Current hor. particle velocity (m/s)	0.65	0.65	0.73	0.83
Current velocity ratio (-)	0.5	0.5	0.5	0.5
Span frequency (1/s)	2.52	2.52	2.84	3.21
Allowable span length (m)	22.9	22.9	23.0	21.6
26m WD				
Wave hor. particle velocity (m/s)	0.53	0.53	0.60	0.69
Current hor. particle velocity (m/s)	0.53	0.53	0.60	0.69
Current velocity ratio (-)	0.5	0.5	0.5	0.5
Span frequency (1/s)	2.07	2.07	2.35	2.69
Allowable span length (m)	25.2	25.2	25.3	23.7

Table 7-7 Allowable span due to in-line VIV

There is relatively little difference between the allowable span in the various conditions. This is because the VIV phenomenon is governed by the steady current, which is of similar magnitude at all locations. The selected limit of current flow velocity ratio, α=0.5, is also a significant factor. If this is increased to α=0.6, the allowable span (in-line VIV) for installation condition at 26m water depth is increased from 25.2m to 27.6m. Selecting a higher current flow velocity ratio requires that the pipeline amplitude response is further investigated, this is left to the detail design phase.

Cross flow VIV:

Property	Installation (flooded)	Hydrotest	Operation LC1	Operation LC2
8m WD				
Wave hor. particle velocity (m/s)	1.3	1.3	1.6	1.5
Current hor. particle velocity (m/s)	0.71	0.71	0.79	0.81
Reynolds nr. (-)	$2.07 * 10^6$	$2.07 * 10^6$	$2.47 * 10^6$	$2.46 * 10^6$
Reduced velocity limit (-)	3.85	3.85	3.85	3.85
Span frequency (1/s)	1.01	1.01	1.21	1.21
Allowable span length (m)	36.0	36.0	35.3	35.3
17m WD				
Wave hor. particle velocity (m/s)	1.33	1.33	2.08	1.76
Current hor. particle velocity (m/s)	0.65	0.65	0.73	0.83
Reynolds nr. (-)	$2.03 * 10^6$	$2.03 * 10^6$	$2.90 * 10^6$	$2.66 * 10^6$
Reduced velocity limit (-)	3.85	3.85	3.85	3.85
Span frequency (1/s)	1.00	1.00	1.42	1.30
Allowable span length (m)	36.4	36.4	32.6	34.0
26mWD				
Wave hor. particle velocity (m/s)	1.35	1.35	2.56	2.01
Current hor. particle velocity (m/s)	0.53	0.53	0.60	0.69
Reynolds nr. (-)	$1.94 * 10^6$	$1.94 * 10^6$	$3.26 * 10^6$	$2.78 * 10^6$
Reduced velocity limit (-)	3.85	3.85	3.85	3.85
Span frequency (1/s)	0.95	0.95	1.60	1.36
Allowable span length (m)	37.2	37.2	30.7	33.2

Table 7-7 Allowable span due to cross-flow VIV

8. Upheaval Buckling – Analytical

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 relation between minimum required cover height and the imperfection height (out-of-straightness) will be established in accordance with ref. [11].

Parameters used in the assessment of upheaval buckling are the dimensionless imperfection length parameter (Φ_L):

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

Where:

L	=	exposure length (m)
N_e	=	effective axial compressive force (N)
EI	=	bending stiffness (N m^2)

And the dimensionless maximum download parameter (Φ_w):

$$\Phi_w = \frac{w \cdot E \cdot I}{\Delta_{calc} \cdot N_e^2}$$

Where:

w	=	required download [N/m]
Δ_{calc}	=	imperfection height [m]

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

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

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

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

In cohesionless soils the uplift resistance (q) due to the cover of the pipe can be calculated from:

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

Where:

γ	=	effective under water weight of soil (N/m^3)
H	=	depth of cover (m)
OD	=	outside diameter of pipe (m)
f	=	uplift coefficient 0.5 for dense material 0.1 for loose material

The calculated required download (w) shall be smaller than the actual combination of the submerged weight and uplift resistance of the pipeline.

The simplified method from Reference [11] is conservative, in that it does not model a number of mitigating factors such as:

- The finite axial stiffness of the pipeline, which determines how rapidly the axial force diminishes as the pipeline moves upwards
- The pipeline resistance to axial movement through the soil determines how far the pipeline can slide towards a developing buckle.

Both the above factors may cause progressive upheaval buckling, as predicted by the analysis method in Reference [11], not to occur.

Further, the sinusoidal imperfection profile assumed in the model is envisaged to yield conservative download requirements.

8.1. Results

The results are presented as the minimum safe length for a given imperfection height and cover height, at the maximum operational temperature of 43°C and operational pressure of 95 barg. An ‘x’ denotes that there is no risk of upheaval buckling for the given condition. An excerpt of the calculations is presented in Appendix D.

Minimum 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]		9929	9232	8553	7889	7243	6613	6000	5403	4823	4260	3714	3184	2671	2174
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	x
	0.15	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	0.2	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	0.25	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	0.3	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	0.35	x	x	x	x	x	x	x	x	x	x	x	x	x	42.6
	0.4	x	x	x	x	x	x	x	x	x	x	x	x	x	50.9
	0.45	x	x	x	x	x	x	x	x	x	x	x	x	46.3	56.3
	0.5	x	x	x	x	x	x	x	x	x	x	x	x	51.8	70.5
	0.55	x	x	x	x	x	x	x	x	x	x	x	47.7	56.0	78.0
	0.6	x	x	x	x	x	x	x	x	x	x	43.0	52.1	68.2	84.0
	0.65	x	x	x	x	x	x	x	x	x	x	48.4	55.7	75.2	89.2
	0.7	x	x	x	x	x	x	x	x	x	44.5	52.1	65.4	80.5	94.0
	0.75	x	x	x	x	x	x	x	x	x	48.7	55.2	72.6	85.1	98.5
	0.8	x	x	x	x	x	x	x	x	45.2	51.9	58.0	77.6	89.4	>100
	0.85	x	x	x	x	x	x	x	x	48.8	54.6	70.1	81.8	93.3	>100
	0.9	x	x	x	x	x	x	x	45.5	51.6	57.1	74.9	85.6	97.0	>100
	0.95	x	x	x	x	x	x	x	48.7	54.1	67.3	78.8	89.1	>100	>100
	1	x	x	x	x	x	x	45.6	51.2	56.3	72.3	82.4	92.4	>100	>100

Table 8-1 Out of straightness table

9. Bottom Roughness Analysis

9.1. General

The pipeline route experiences significant undulations in the sea bed, which may create free spans of the pipeline. In order to assess if the pipeline spans are greater than allowed in the time between installation and burial, a bottom roughness analysis. A FEA model is created which incorporates the surveyed sea floor profile, the interaction between pipe and sea floor, and the structural behaviour of the pipeline.

The finite element calculation is carried out using industry proven software package ANSYS. The analysis is at this stage of the design is limited to identifying locations with more than critical span length between installation and burial, no modifications to the sea floor are determined.

The pipeline will be modelled by ANSYS' PIPE288 element. This is a 3D pipe element consisting of 3 'layers': an internal layer to account for the weight of the internal fluid, a structural layer used for the structural calculations, and an outer layer to account for the coating. Additionally, the buoyancy of the displaced seawater is accounted for.

The pipeline is modelled with an element length of 1 m and accounts for undulations in the vertical direction. Pipe-soil interaction is simulated using three independent non-linear spring elements 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.

Seabed roughness will be simulated by displacing the vertical springs representing the soil bearing capacity to the correct depth based on the bathymetric data and allowing the pipe to move and rest on the vertical springs.

When the support force of a vertical spring is 0, a free span is identified. Similar succeeding points indicate a larger span. The length of the free span is determined by subtracting the coordinates of the beginning of the span from the coordinates of the span end. Based on the acceptable spans identified in this document, the locations where spans are larger than the critical span are found and reported.

9.2. Definition of Soil Springs

The characteristics of the springs which simulate the pipe-soil interaction are defined through non-linear force-deflection curves. These force-deflection curves describe the frictional restraint provided by the soil to the pipeline in axial, lateral and vertical direction.

Axial and lateral restraint for the unburied pipeline is included as Coulomb friction. The amount of restraint per length of pipeline depends on the friction coefficient and the submerged weight of the pipeline. A friction coefficient of 0.6 was used in both directions, this excludes the effect of soil berms created by lateral movement of the pipeline. In accordance with DNV-RP-F109, the friction coefficient of a pipe on sand is set to 0.6. The maximum friction force is only reached when a nominal displacement has been reached, the mobilization displacement. In the present analysis, mobilization displacement is set to 5 mm. A third point in the spring reaction diagram is set at a displacement of 1m with a reaction force of 1.001 time the maximum friction force, this prevents extrapolation of the first section of the spring slope.

Vertical support follows from the bearing capacity of the idealized 2D strip foundation theory. A touchdown lay factor k_{lay} of 2 has been considered during the installation load case, according to DNV-RP-F114, ref [12]. The 'installation' type supports do not provide resistance against upwards movement of the pipe.

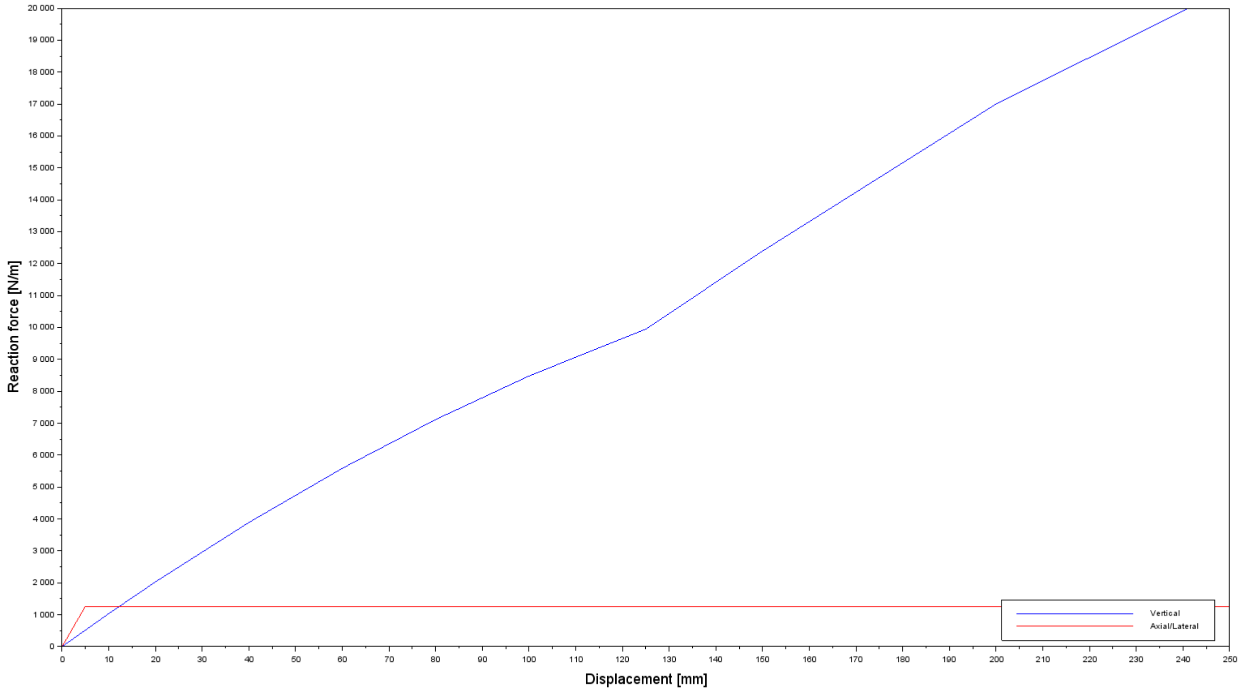


Figure 8-1 Vertical and axial support

9.3. Results

The result of pipeline installation on the as-surveyed sea bed profile is given in Table 8-1, and Figures 8-2 through 8-5. Two (2) spans longer than 20 m were found. If the critical span criterium is set as 25m between KP0 and KP2, 23m between KP2 and KP10, and 22 m from KP10 to the end of the pipeline, only the span of 39m between KP0.048-0.087 violates these criteria. These criteria are based on on the 1-year environmental conditions, for the installation and hydrotest condition.

Table 8-1 Overview largest spans

Span #	Start of span [m]	End of span [m]	Span length [m]	Span criterium [m]
1	48	87	39	<25m NOT OK
2	5.749	5.772	23	<23m OK

The design criterion of span length is exceeded by span 1. Nevertheless it should be noted that the gap at mid span is only 2cm between the pipeline and the seabed. Additional investigations are left for the detail design phase of the pipeline with the aim to remove the need for sea bed modifications.

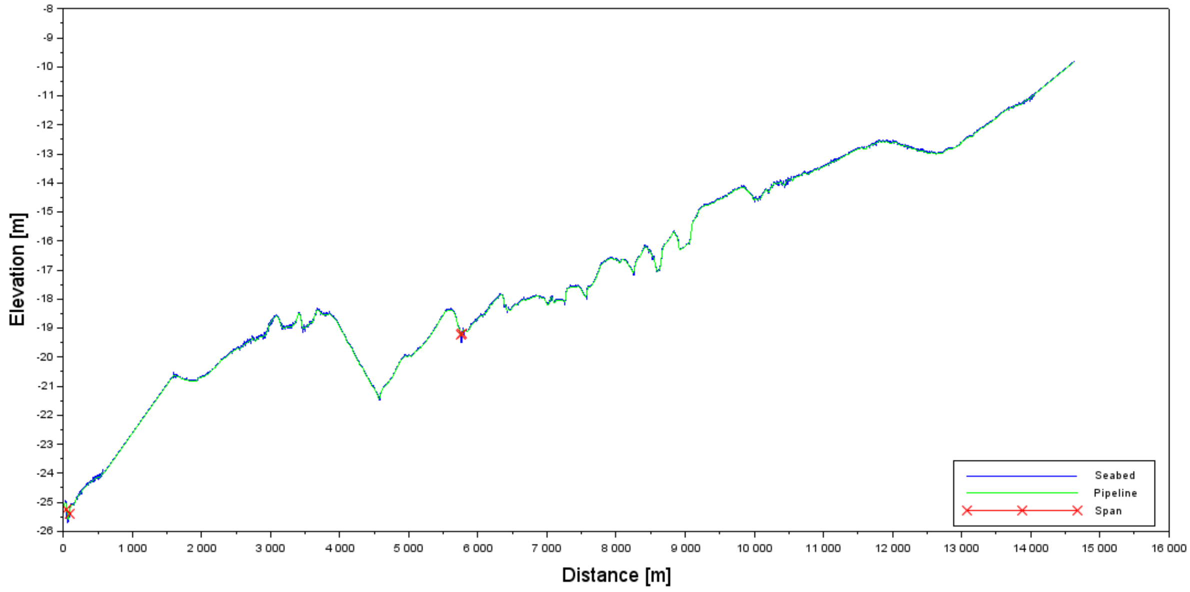


Figure 8-2 Pipeline on sea floor, complete route

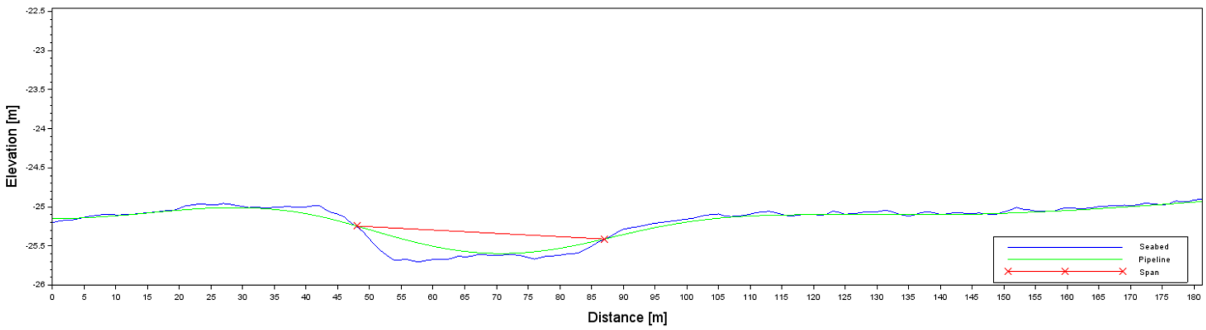


Figure 8-3 Pipeline on sea floor – section at KP 0.048 with spans length =39m (25m allowed)

It should be noted that the gap at mid span is only 2cm between the pipeline and the seabed.

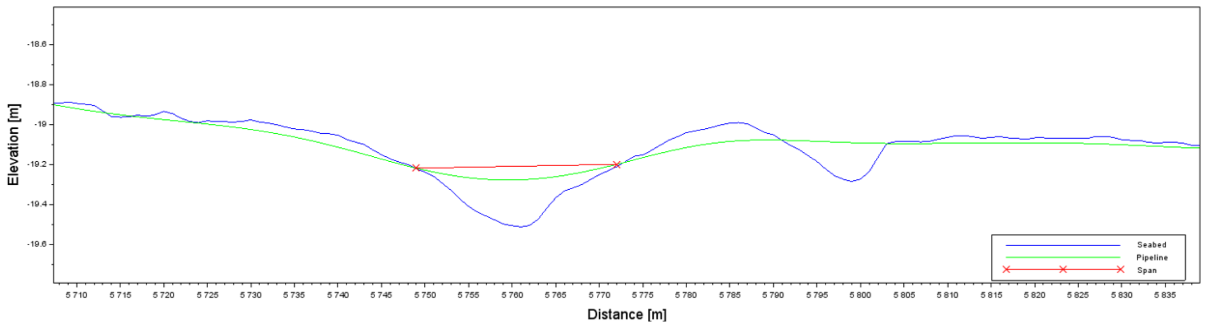


Figure 8-4 Pipeline on sea floor – section at KP 5.749 with spans length =23m (23m allowed)

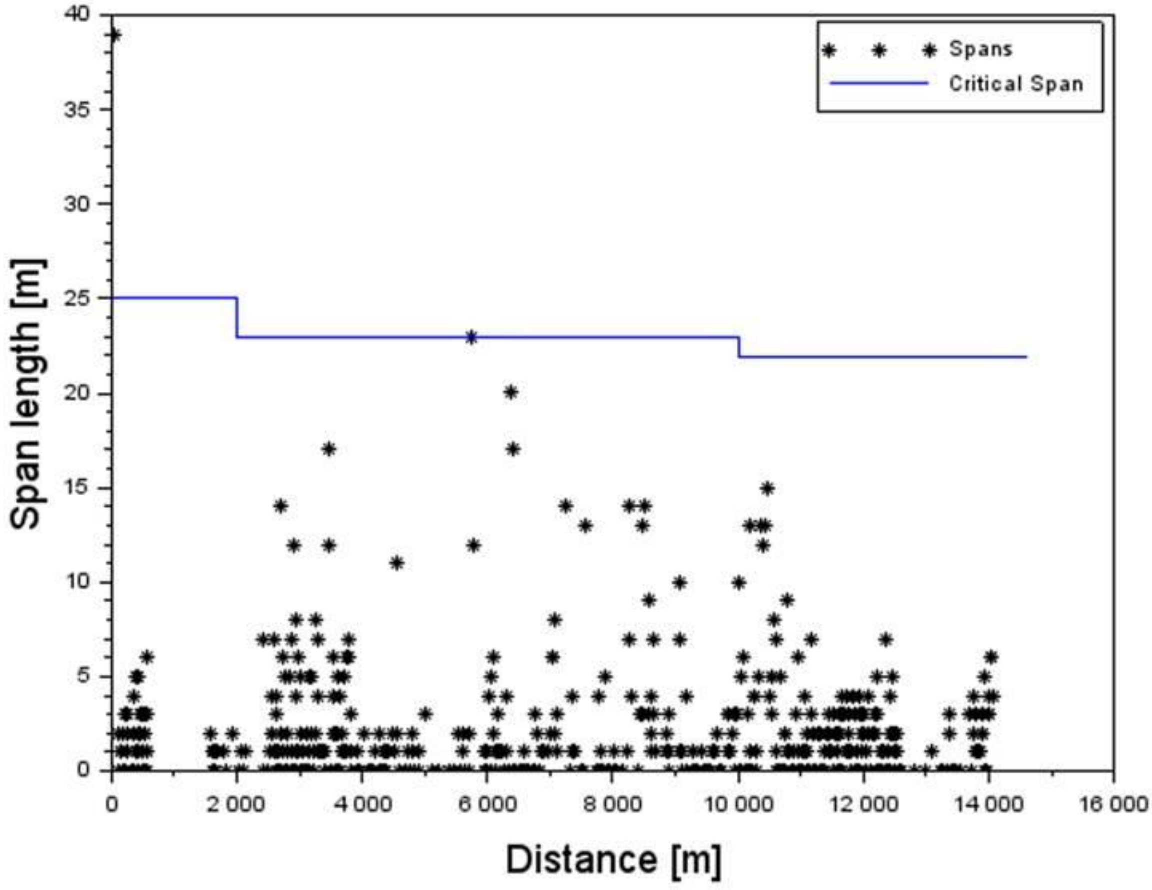


Figure 8-5 Overview of all spans and critical span

A. Wall Thickness Analysis

The following Wall Thickness Analyses were performed:

- 19018-60-CAL-01001-01-01 20” x 20.6 mm – inside 500m zone
- 19018-60-CAL-01001-01-01 20” x 20.6 mm – outside 500m zone

(4 pages)

Project	**: N05-A Pipeline basic design**
Project #	: 19018
Subject	: Wall thickness calculation N05-A Pipeline
File #	: #N/A
Client	: ONE-Dyas
Client File #	:

enersea

Originator	: HvH	Checked	: PF
Date	: 21.10.2019		
Revision	: 01		

20" Pipeline - Inside 500m zone

Material properties

Material			=	L360NB	
Design temperature		T_d	=	50	°C
Yield at ambient temperature		R_e	=	360.00	N/mm^2
Yield at design temperature		R_{ed}	=	360.00	N/mm^2
Material factor (Table 4 NEN 3656)		γ_m	=	1.10	-
Allowable stress	$\sigma_v = \frac{R_{ed}}{\gamma_m}$	σ_v	=	327.27	N/mm^2

Pipeline properties

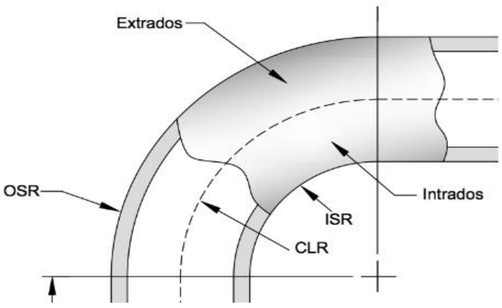
Outside diameter		OD	=	508	mm
Design pressure		P_d	=	111.1	barg
Minimum outside presssure		P_o	=	0	barg
Fabrication Tolerance		f_{tol}	=	7.3	%
Corrosion allowance		CA	=	3	mm
Pipeline within the 500 meter zone?				y	(Y or N)
Load factor (Table 3 NEN 3656): 1,25 outside 500m zone; 1,364 inside 500m zone		γ_s	=	1.364	-
Bend radius				2540	mm
Fabrication tolerance bends		f_{tolB}	=	7.3	%
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): $d_{min} = \frac{\gamma_m \cdot \gamma_s \cdot P_d^* \cdot D_e}{2 \cdot R_e(T_d) + \gamma_m \cdot \gamma_s \cdot P_d^*}$ = 11.50 mm

Inside bend = 12.13 mm

Outside bend = 10.97 mm



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

Straight part / along bend radius @ CLR	=	14.50	mm
Inside bend @ ISR	=	15.13	mm
Outside bend @ OSR	=	13.97	mm

Selected nominal wall thickness = 20.6 mm

Project	**:**	**N05-A Pipeline basic design**
Project #	**:**	19018
Subject	**:**	Wall thickness calculation N05-A Pipeline
File #	**:**	#N/A
Client	**:**	ONE-Dyas
Client File #	**:**	

Originator	: HvH		Checked	: PF
Date	: 21.10.2019			
Revision	: 01			

20" Pipeline - Inside 500m zone

Hoop stress

Hoop stress straight parts $\sigma_{hoop} = \frac{\gamma_s \cdot P_d^* \cdot (D_e - d_{min})}{2 \cdot d_{min}}$ = 231.56 N/mm^2

Hoop stress inside bend $\sigma_{hoop}(BI) = \frac{2 \cdot R - \frac{1}{2} \cdot D_e}{2 \cdot R - D_e} \cdot \sigma_{hoop}$ = 244.42 N/mm^2

Hoop stress outside bend $\sigma_{hoop}(BO) = \frac{2 \cdot R + \frac{1}{2} \cdot D_e}{2 \cdot R + D_e} \cdot \sigma_{hoop}$ = 221.03 N/mm^2

Stress Check

Hoop stress (N/mm2)	Occurring	Allowable
Straight parts	231.56	327.27
Inside bend	244.42	327.27
Outside bend	221.03	327.27

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 $P_{T,min} = C_p \cdot P_d \cdot \frac{R_e(20^\circ C)}{R_e(T_d)}$ = 144.43 barg

Maximum allowable hydrotest pressure $P_{T,max} = \frac{2 \cdot d_{nom} \cdot (1 - f_{tol}) \cdot R_e(20^\circ C)}{(D_e - d_{nom} \cdot (1 - f_{tol}))}$ = 281.23 barg

Mill test pressure $P_{T,mill} = 0.9 \cdot \frac{2 \cdot R_e \cdot d_{nom}}{D_e}$ = 262.77 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.

Project	**:**	**N05-A Pipeline basic design**
Project #	**:**	19018
Subject	**:**	Wall thickness calculation N05-A Pipeline
File #	**:**	19018-60-CAL-01001-02-01a_Wall thickness_20x20.6_L360_outside 500m.xlsx
Client	**:**	ONE-Dyas
Client File #	**:**	

Originator	: HvH	Checked	: PF
Date	: 21.10.2019		
Revision	: 01		

20" Pipeline - Outside 500m zone

Material properties

Material		=	L360NB	
Design temperature	T_d	=	50	°C
Yield at ambient temperature	R_e	=	360.00	N/mm^2
Yield at design temperature	R_{ed}	=	360.00	N/mm^2
Material factor (Table 4 NEN 3656)	γ_m	=	1.10	-
Allowable stress $\sigma_v = \frac{R_{ed}}{\gamma_m}$	σ_v	=	327.27	N/mm^2

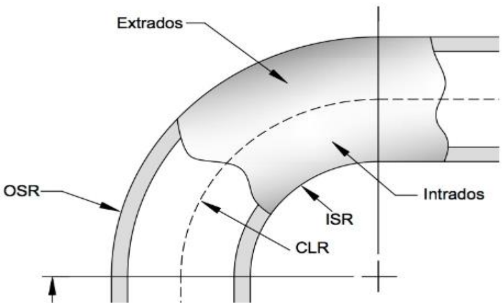
Pipeline properties

Outside diameter	OD	=	508	mm
Design pressure	P_d	=	111.1	barg
Minimum outside presssure	P_o	=	0	barg
Fabrication Tolerance	f_{tol}	=	7.3	%
Corrosion allowance	CA	=	3	mm
Pipeline within the 500 meter zone?			n	(Y or N)
Load factor (Table 3 NEN 3656): 1,25 outside 500m zone; 1,364 inside 500m zone	γ_s	=	1.250	-
Bend radius			2540	mm
Fabrication tolerance bends	f_{tolB}	=	7.3	%
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):	=	10.55	mm
Inside bend	=	11.14	mm
Outside bend	=	10.07	mm



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

Straight part / along bend radius @ CLR	=	13.55	mm
Inside bend @ ISR	=	14.14	mm
Outside bend @ OSR	=	13.07	mm

Selected nominal wall thickness = 20.6 mm

Project	**: N05-A Pipeline basic design**
Project #	: 19018
Subject	: Wall thickness calculation N05-A Pipeline
File #	: 19018-60-CAL-01001-02-01a_Wall thickness_20x20.6_L360_outside 500m.xlsx
Client	: ONE-Dyas
Client File #	:

Originator	: HvH	Checked	: PF
Date	: 21.10.2019		
Revision	: 01		

20" Pipeline - Outside 500m zone

Hoop stress

Hoop stress straight parts $\sigma_{hoop} = \frac{\gamma_s \cdot P_d^* \cdot (D_e - d_{\min})}{2 \cdot d_{\min}}$ = 212.20 N/mm^2

Hoop stress inside bend $\sigma_{hoop}(BI) = \frac{2 \cdot R - \frac{1}{2} \cdot D_e}{2 \cdot R - D_e} \cdot \sigma_{hoop}$ = 223.99 N/mm^2

Hoop stress outside bend $\sigma_{hoop}(BO) = \frac{2 \cdot R + \frac{1}{2} \cdot D_e}{2 \cdot R + D_e} \cdot \sigma_{hoop}$ = 202.56 N/mm^2

Stress Check

Hoop stress (N/mm2)	Occurring	Allowable
Straight parts	212.20	327.27
Inside bend	223.99	327.27
Outside bend	202.56	327.27

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 $P_{T,\min} = C_p \cdot P_d \cdot \frac{R_e(20^\circ C)}{R_e(T_d)}$ = 144.43 barg

Maximum allowable hydrotest pressure $P_{T,\max} = \frac{2 \cdot d_{nom} \cdot (1 - f_{tol}) \cdot R_e(20^\circ C)}{(D_e - d_{nom} \cdot (1 - f_{tol}))}$ = 281.23 barg

Mill test pressure $P_{T,mill} = 0.9 \cdot \frac{2 \cdot R_e \cdot d_{nom}}{D_e}$ = 262.77 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.

B. Buckling & Collapse Analysis

The following buckling and collapse analyses were performed:

- 19018-60-CAL-01003-01-01 Buckling & Collapse calculation – 26m – operation
- 19018-60-CAL-01003-02-01 Buckling & Collapse calculation – 26m – installation flooded
- 19018-60-CAL-01003-03-01 Buckling & Collapse calculation – 26m - hydrotest
- 19018-60-CAL-01003-04-01 Buckling & Collapse calculation – 8m - operation
- 19018-60-CAL-01003-05-01 Buckling & Collapse calculation – 8m - installation flooded
- 19018-60-CAL-01003-06-01 Buckling & Collapse calculation – 8m - hydrotest
- 19018-60-CAL-01003-07-01 Buckling & Collapse calculation – 17m - operation
- 19018-60-CAL-01003-08-01 Buckling & Collapse calculation – 17m - installation flooded
- 19018-60-CAL-01003-09-01 Buckling & Collapse calculation – 17m - hydrotest

(66 pages) only 26m with Stokes+hydroload pages

Project	**: N05-A Pipeline design**	
Project #	: 19018	
Subject	: Buckling and Collapse	
File #	: 19018-60-CAL-01003-01-01 - Buckling & Collapse calculations - 26m - operation.xlsx	
Client	: ONE-Dyas	
Client File #	:	

Originator	: EvW	Checked	:
Date	: 24/01/2020		
Revision	: 01		

Buckling and Collapse - 20in x 20.62mm - Operational

Situation

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

4
Operational

	Pressure (barg)	Temperature (deg. C)
Installation (P_{in}, T_{in})	2	15
Design (P_d, T_d)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm

Piggyback

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

Coating data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Material		=	L360NB	
Design temperature		T_d =	50	°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			96.1	kg/m^3
Pipeline content density used for this case:	Operational		96.1	kg/m^3
Pipeline Weights				
Pipeline weight in air	$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$	$W_{pl,a}$ =	2636.6	N/m
Piggyback weight in air		$W_{pg,a}$ =	0.0	N/m
Buoyancy force pipeline	$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$	$F_{B,pl}$ =	2086.5	N/m
Buoyancy force piggyback		$F_{B,pb}$ =	0.0	N/m
Submerged pipeline weight,empty		$W_{pl,s,e}$ =	388.8	N/m
Submerged piggyback weight		$W_{pg,s}$ =	0.0	N/m
Total submerged bundle weight,empty		$W_{T,s,e}$ =	388.8	N/m
Total submerged bundle weight,water filled		$W_{T,s,f}$ =	2109.4	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} =	29.68	m LAT
Minimum water depth		WD_{min} =	26	m LAT
Other water depth (to be used for calculations)		WD =	26	m LAT
Storm surge, RP1 yr		ss_{1yr} =	-1.02	m LAT
Storm surge, RP100 yr		ss_{100yr} =	-1.79	m LAT
Storm surge water level	SSWL = WD + ss	SSWL =	24.21	m LAT
Highest Astronomical Tide		HAT =	2.72	m
Waves (H_{max} & T_{max}):				
Maximum wave height, RP1 yr - installation/hydrotes		$H_{max,1}$ =	11.4	m
Associated maximum wave period, RP1 yr		$T_{ass,1}$ =	10.1	s
Maximum wave height, RP100 yr - operational		$H_{max,100}$ =	16.9	m
Associated maximum wave period, RP100 yr		$T_{ass,100}$ =	11.5	s

Project	: **N05-A Pipeline design**			
Project #	: 19018			
Subject	: Buckling and Collapse			
File #	: 19018-60-CAL-01003-01-01 - Buckling & Collapse calculations - 26m - operation.xlsx			
Client	: ONE-Dyas			
Client File #	:			
Originator	: EvW		Checked	:
Date	: 24/01/2020			
Revision	: 01			

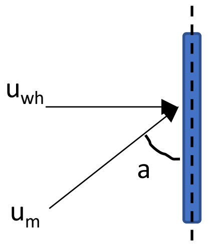
Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$$\frac{H_{max}}{g \cdot T_z^2} = 0.0130$$

$$\frac{SWL}{g \cdot T_z^2} = 0.0187$$

Wave theory selected:

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



Maximum wave particle velocity	u_{wm} =	4.00	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	4.00	m/s

Current:

Height above seabed at which velocity is known	z^* =	2	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.74	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.84	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	0.96	m/s
Current velocity at reference height	U_{czr} =	0.96	m/s
Angle of attack relative to pipeline axis	α_{uc} =	90	deg
Horizontal current velocity ⊥ to P/L	$\frac{7}{8} \cdot U_{czr} \cdot \left(\frac{OD_{nom}}{z_r}\right)^{1/7} \cdot \sin(\alpha_{uc}) = u_{ch}$ =	0.69	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 — 4320 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):	$P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3$ =	34.0	N/mm^2
External plastic pipe collapse pressure (P_p)	$P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$ =	29.2	N/mm^2
External implosion pipe collapse pressure (P_c):	P_c =	16.0	N/mm^2
Maximum water column above mudline (WC_{max})	$WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT$ =	40.85	m
		0.4085	N/mm^2
Actual external pressure (P_L)	$WC_{max} + SC_{pres}$ =	0.42	N/mm^2

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) $M_c = D_g^2 d_n R_e$ = 1.8E+09 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 ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm
= 1.256E+06 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 = 13.6 -

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm
= 9.994E+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 =	389	N/m
$F_D + F_I$ =	4320	N/m
g_w =	1.1	-
g_h =	1.2	-

Table 3 - NEN3656

q = 5202 N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 9.99E+05 N·m

Maximum span length, L_{max} = 43.8 m

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	=	46	-
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 = 169.3 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: 0.0005 < 0.0030 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 23.9 **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	=	-2.05E+06	N

$L_{max,bb}$ = 61.7 m

Stokes 5th order wave theory

Water depth	WD =	26	m (LAT)
Storm surge	ss =	-1.79	m
Storm surge water level	$SWL = WD + ss$ =	24.21	m
Wave height	H =	16.9	m
Wave period	T =	11.5	s
Grav. Acceleration	g =	9.81	m/s^2
Deep water wave length	$L_o = \frac{g \cdot T^2}{2 \cdot \pi}$ =	206.5	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 **184.228** **m**

$$A = SWL / L_O = 0.1172$$

$$B = \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) = 0.0891$$

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

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

$$D = (C_1 \cdot B)^2 - 4 \cdot (C_2 \cdot B) \cdot (-(A - B)) = 0.5724$$

	-	eq. (I)	eq. (II)
λ1	0.227	-0.0004	0.0000
λ2	Numerator of X < 0		
λ3	-0.227	4.3864	0.0000
λ4	Numerator of X < 0		

Item	Formula	Value	Unit
s	$s = \sinh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	0.9228	-
c	$c = \cosh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.3607	-
A11	$A_{11} = \frac{1}{s} =$	1.0837	-
A13	$A_{13} = \frac{-c^2 \cdot (5 \cdot c^2 + 1)}{8 \cdot s^5} =$	-3.5482	-
	$A_{15} = -\frac{1184 \cdot c^{10} - 1440 \cdot c^8 - 1992 \cdot c^6 + 2641 \cdot c^4 - 249 \cdot c^2 + 18}{1536 \cdot s^{11}} =$	-7.5755	-
A22	$A_{22} = \frac{3}{8 \cdot s^4} =$	0.5172	-
A24	$A_{24} = \frac{192 \cdot c^8 - 424 \cdot c^6 - 312 \cdot c^4 + 480 \cdot c^2 - 17}{768 \cdot s^{10}} =$	-1.8403	-
A33	$A_{33} = \frac{13 - 4 \cdot c^2}{64 \cdot s^7} =$	0.1534	-
	$A_{35} = \frac{512 \cdot c^{12} + 4224 \cdot c^{10} - 6800 \cdot c^8 - 12808 \cdot c^6 + 16704 \cdot c^4 - 3154 \cdot c^2 - 107}{4096 \cdot s^{13} \cdot (6 \cdot c^2 - 1)} =$	0.1815	-
A44	$A_{44} = \frac{80 \cdot c^6 - 816 \cdot c^4 + 1338 \cdot c^2 - 197}{1536 \cdot s^{10} \cdot (6 \cdot c^2 - 1)} =$	-0.0013	-

$$A_{55} = -\frac{2880\cdot c^{10} - 72480\cdot c^8 + 324000\cdot c^6 - 432000\cdot c^4 + 163470\cdot c^2 - 16245}{61440\cdot s^{11}\cdot(6\cdot c^2 - 1)\cdot(8\cdot c^4 - 11\cdot c^2 + 3)} =$$ -0.0282 -

B22 $$B_{22} = \frac{(2\cdot c^2 + 1)\cdot c}{4\cdot s^3} =$$ 2.0361 -

B24 $$B_{24} = \frac{c\cdot(272\cdot c^8 - 504\cdot c^6 - 192\cdot c^4 + 322\cdot c^2 + 21)}{384\cdot s^9} =$$ -0.3177 -

B33 $$B_{33} = \frac{3\cdot(8\cdot c^6 + 1)}{64\cdot s^6} =$$ 3.9311 -

$$B_{35} = \frac{88128\cdot c^{14} - 208224\cdot c^{12} + 70848\cdot c^{10} + 54000\cdot c^8 - 21816\cdot c^6 + 6264\cdot c^4 - 54\cdot c^2 - 81}{12288\cdot s^{12}\cdot(6\cdot c^2 - 1)} =$$
= 5.1509 -

B44 $$B_{44} = c\cdot\frac{768\cdot c^{10} - 488\cdot c^8 - 48\cdot c^6 + 48\cdot c^4 + 106\cdot c^2 - 21}{384\cdot s^9\cdot(6\cdot c^2 - 1)} =$$ 7.9561 -

$$B_{55} = \frac{192000\cdot c^{16} - 26720\cdot c^{14} + 83680\cdot c^{12} + 20160\cdot c^{10} - 7280\cdot c^8 + 7160\cdot c^6 - 1800\cdot c^4 - 1050\cdot c^2 + 225}{12288\cdot s^{10}\cdot(8\cdot c^4 - 11\cdot c^2 + 3)\cdot(6\cdot c^2 - 1)} =$$
= 19.0981 -

C1 $$C_1 = \frac{8\cdot c^4 - 8\cdot c^2 + 9}{8\cdot s^4} =$$ 3.7260 -

$$C_2 = \frac{3840\cdot c^{12} - 4096\cdot c^{10} + 2592\cdot c^8 - 1008\cdot c^6 + 5944\cdot c^4 - 1830\cdot c^2 + 147}{512\cdot s^{10}\cdot(6\cdot c^2 - 1)} =$$ 46.0838 -

C3 $$C_3 = -\frac{1}{4\cdot c\cdot s} =$$ -0.1991 -

C4 $$C_4 = \frac{12\cdot c^8 + 36\cdot c^6 - 162\cdot c^4 + 141\cdot c^2 - 27}{192\cdot c\cdot s^9} =$$ 0.3806 -

K1 $$K_1 = \lambda\cdot A_{11} + \lambda^3\cdot A_{13} + \lambda^5\cdot A_{15} =$$ 0.2001 -

K2	$K_2 = \lambda^2 \cdot A_{22} + \lambda^4 \cdot A_{24} =$	0.0218	-
K3	$K_3 = \lambda^3 \cdot A_{33} + \lambda^5 \cdot A_{35} =$	0.0019	-
K4	$K_4 = \lambda^4 \cdot A_{44} =$	0.0000	-
K5	$K_5 = \lambda^5 \cdot A_{55} =$	0.0000	-

Project	**:**	**N05-A Pipeline design**
Project #	**:**	19018
Subject	**:**	Buckling and Collapse
File #	**:**	19018-60-CAL-01003-01-01 - Buckling & Collapse calculations - 26m - operation.xlsx
Client	**:**	ONE-Dyas
Client File #	**:**	

Originator	: EvW	Checked	:
Date	: 24/01/2020		
Revision	: 01		

Horizontal wave particle velocities

Water depth at which data required, z (w.r.t. seabed) 0.5080 m

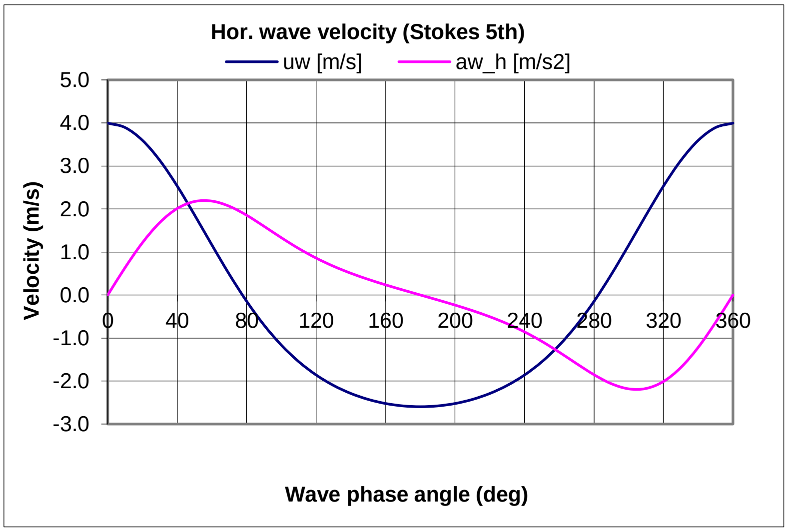
Horizontal velocity, u_w

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

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	3.9954	0.0000
10.00	3.8927	0.6377
20.00	3.5942	1.2167
30.00	3.1271	1.6861
40.00	2.5326	2.0102
50.00	1.8601	2.1734
60.00	1.1605	2.1823
70.00	0.4796	2.0627
80.00	-0.1478	1.8534
90.00	-0.6996	1.5968
100.00	-1.1669	1.3301
110.00	-1.5511	1.0793
120.00	-1.8596	0.8578
130.00	-2.1025	0.6679
140.00	-2.2893	0.5054
150.00	-2.4276	0.3633
160.00	-2.5229	0.2353
170.00	-2.5788	0.1156
180.00	-2.5972	0.0000
190.00	-2.5788	-0.1156
200.00	-2.5229	-0.2353



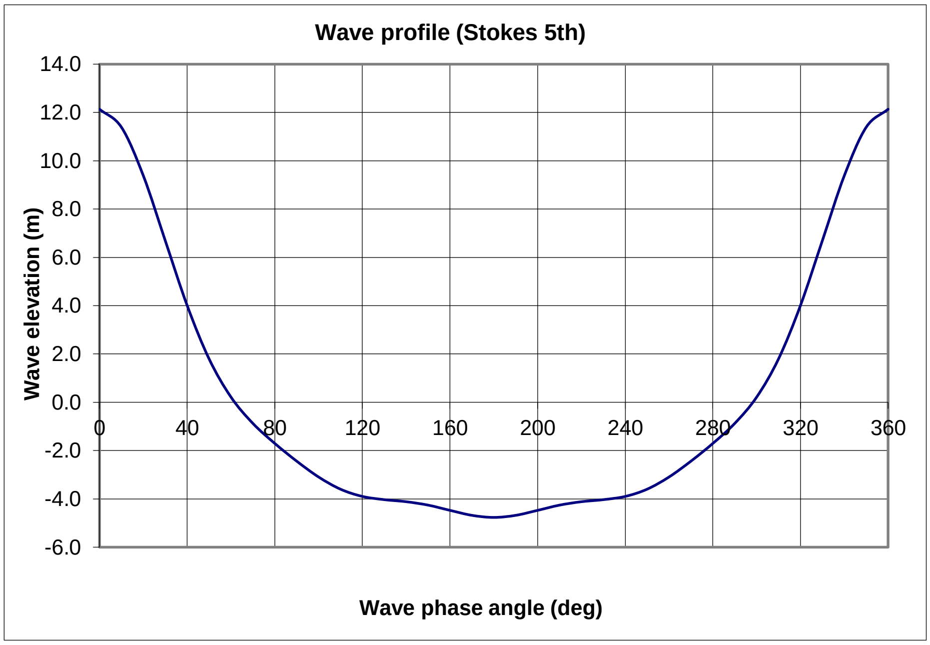
210.00	-2.4276	-0.3633
220.00	-2.2893	-0.5054
230.00	-2.1025	-0.6679
240.00	-1.8596	-0.8578
250.00	-1.5511	-1.0793
260.00	-1.1669	-1.3301
270.00	-0.6996	-1.5968
280.00	-0.1478	-1.8534
290.00	0.4796	-2.0627
300.00	1.1605	-2.1823
310.00	1.8601	-2.1734
320.00	2.5326	-2.0102
330.00	3.1271	-1.6861
340.00	3.5942	-1.2167
350.00	3.8927	-0.6377
360.00	3.9954	0.0000

U_{wm} = max. wave particle velocity = 4.00 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	12.1350
10.00	11.3883
20.00	9.3802
30.00	6.6968
40.00	4.0097
50.00	1.7992
60.00	0.2151
70.00	-0.8738
80.00	-1.7036
90.00	-2.4374
100.00	-3.0936
110.00	-3.5987
120.00	-3.8987
130.00	-4.0330
140.00	-4.1177
150.00	-4.2594
160.00	-4.4749
170.00	-4.6819
180.00	-4.7680
190.00	-4.6819
200.00	-4.4749
210.00	-4.2594
220.00	-4.1177
230.00	-4.0330
240.00	-3.8987
250.00	-3.5987
260.00	-3.0936
270.00	-2.4374
280.00	-1.7036
290.00	-0.8738
300.00	0.2151
310.00	1.7992
320.00	4.0097
330.00	6.6968
340.00	9.3802
350.00	11.3883
360.00	12.1350



Project	**:**	**N05-A Pipeline design**
Project #	**:**	19018
Subject	**:**	Buckling and Collapse
File #	**:**	19018-60-CAL-01003-02-01 - Buckling & Collapse calculations - 26m - installation flooded.xlsx
Client	**:**	ONE-Dyas
Client File #	**:**	19018-60-CAL-01003-02-01 - Buckling & Collapse calculations - 26m - installation flooded.xlsx

Originator	: EvW	Checked	:
Date	: 24/01/2020		
Revision	: 01		

Buckling and Collapse - 20in x 20.62mm - 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)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm

Piggyback

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

Coating data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Project	:	**N05-A Pipeline design**
Project #	:	19018
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Originator	: EvW	Checked :
Date	: 24/01/2020	
Revision	: 01	

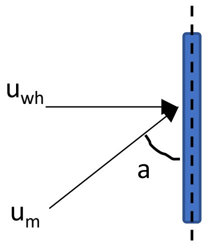
Material		=	L360NB	
Design temperature		T_d =	15	°C
Yield at ambient temperature		R_e =	360.00	N/mm^2
Yield at design temperature		R_{ed} =	360.00	N/mm^2
Density		ρ_{st} =	7850	kg/m^3
Youngs modulus		E_s =	210000	N/mm^2
Poisson's ratio		u =	0.3	-
Linear thermal expansion coefficient		a =	1.16E-05	$m/m/^oC$
Contents				
Sea water density			1025	kg/m^3
Pipeline product density			96.1	kg/m^3
Pipeline content density used for this case:	Installation: filled		1025	kg/m^3
Pipeline Weights				
Pipeline weight in air	$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$	$W_{pl,a}$ =	4195.8	N/m
Piggyback weight in air		$W_{pg,a}$ =	0.0	N/m
Buoyancy force pipeline	$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$	$F_{B,pl}$ =	2086.5	N/m
Buoyancy force piggyback		$F_{B,pb}$ =	0.0	N/m
Submerged pipeline weight,empty		$W_{pl,s,e}$ =	388.8	N/m
Submerged piggyback weight		$W_{pg,s}$ =	0.0	N/m
Total submerged bundle weight,empty		$W_{T,s,e}$ =	388.8	N/m
Total submerged bundle weight,water filled		$W_{T,s,f}$ =	2109.4	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} =	29.68	m LAT
Minimum water depth		WD_{min} =	26	m LAT
Other water depth (to be used for calculations)		WD =	26	m LAT
Storm surge, RP1 yr		ss_{1yr} =	-1.02	m LAT
Storm surge, RP100 yr		ss_{100yr} =	-1.79	m LAT
Storm surge water level	SSWL = WD + ss	SSWL =	24.98	m LAT
Highest Astronomical Tide		HAT =	2.72	m
Waves (H_{max} & T_{max}):				
Maximum wave height, RP1 yr - installation/hydrotes		$H_{max,1}$ =	11.4	m
Associated maximum wave period, RP1 yr		$T_{ass,1}$ =	10.1	s
Maximum wave height, RP100 yr - operational		$H_{max,100}$ =	16.9	m
Associated maximum wave period, RP100 yr		$T_{ass,100}$ =	11.5	s

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

$\frac{H_{max}}{g \cdot T_z^2} =$ 0.0114

$\frac{SWL}{g \cdot T_z^2} =$ 0.0250

Wave theory selected:
1. Airy/linear wave; 2. Stokes 5th — **2** — Stokes 5th



Maximum wave particle velocity	u_{wm} =	2.39	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	2.39	m/s

Current:

Height above seabed at which velocity is known	z^* =	2	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.74	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.84	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	0.96	m/s
Current velocity at reference height	U_{czr} =	0.74	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} =	0.53	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 — 1822 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): $P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3 =$ 34.0 N/mm^2

External plastic pipe collapse pressure (P_p): $P_p = \frac{2 R_e d_{nom}}{OD_{nom}} =$ 29.2 N/mm^2

External implosion pipe collapse pressure (P_c): P_c = 16.0 N/mm^2

Maximum water column above mudline (WC_{max}): $WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT =$ 40.85 m
0.4085 N/mm^2

Actual external pressure (P_L): $WC_{max} + SC_{pres} =$ 0.42 N/mm^2

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

Table 4 - NEN3656

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

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

Collapse - bending moment only (K.3.3.5.2)

Buckling bending moment (M_c) $M_c = D_g^2 d_n R_e$ = 1.8E+09 N·mm

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

Table 4 - NEN3656

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

Maximum allowable bending moment ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm
= 1.256E+06 N·m

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

Assessment: $\frac{\gamma_{g,p} \times P_L}{P_c / \gamma_{m,p}} + \left(\frac{\gamma_{g,M} \times M_L}{M_c / \gamma_{m,M}} \right)^n \leq \gamma_M$ **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 =	13.6	-

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm
= 9.994E+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 =	2109	N/m
$F_D + F_I$ =	1822	N/m
g_w =	1.1	-
g_h =	1.2	-
Table 3 - NEN3656		
q =	3188	N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 9.99E+05 N·m

Maximum span length, L_{max} = 56.0 m

Originator	: EvW	Checked	:
Date	: 24/01/2020		
Revision	: 01		

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/mm^2

R_{ed} = 360.00 N/mm^2

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

s_p = 3.1 N/mm^2

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

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 = 23.9 **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 = -8.97E+05 N

$L_{max,bb}$ = 93.1 m

Stokes 5th order wave theory

Water depth	WD =	26	m (LAT)
Storm surge	ss =	-1.02	m
Storm surge water level	$SWL = WD + ss$ =	24.98	m
Wave height	H =	11.4	m
Wave period	T =	10.1	s
Grav. Acceleration	g =	9.81	m/s²
Deep water wave length	$L_o = \frac{g \cdot T^2}{2 \cdot \pi}$ =	159.3	m

Solving for wave length (L) and λ

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

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

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

Estimate actual wave length, L **143.093 m**

$A = SWL / L_O$ = 0.1568

$B = \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right)$ = 0.1395

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

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

$D = (C_1 \cdot B)^2 - 4 \cdot (C_2 \cdot B) \cdot (-(A - B))$ = 0.1581

	-	eq. (I)	eq. (II)
λ1	0.228	0.0005	0.0000
λ2	Numerator of X < 0		
λ3	-0.228	2.8669	0.0000
λ4	Numerator of X < 0		

Item	Formula	Value	Unit
s	$s = \sinh\left(\frac{2\cdot\pi\cdot WL}{L}\right) =$	1.3304	-
c	$c = \cosh\left(\frac{2\cdot\pi\cdot WL}{L}\right) =$	1.6643	-
A11	$A_{11} = \frac{1}{s} =$	0.7516	-
A13	$A_{13} = \frac{-c^2\cdot(5\cdot c^2+1)}{8\cdot s^5} =$	-1.2336	-
	$A_{15} = -\frac{1184\cdot c^{10} - 1440\cdot c^8 - 1992\cdot c^6 + 2641\cdot c^4 - 249\cdot c^2 + 18}{1536\cdot s^{11}} =$	-2.4101	-
A22	$A_{22} = \frac{3}{8\cdot s^4} =$	0.1197	-
A24	$A_{24} = \frac{192\cdot c^8 - 424\cdot c^6 - 312\cdot c^4 + 480\cdot c^2 - 17}{768\cdot s^{10}} =$	0.0907	-
A33	$A_{33} = \frac{13 - 4\cdot c^2}{64\cdot s^7} =$	0.0041	-
	$A_{35} = \frac{512\cdot c^{12} + 4224\cdot c^{10} - 6800\cdot c^8 - 12808\cdot c^6 + 16704\cdot c^4 - 3154\cdot c^2 - 107}{4096\cdot s^{13}\cdot(6\cdot c^2 - 1)} =$	0.1402	-
A44	$A_{44} = \frac{80\cdot c^6 - 816\cdot c^4 + 1338\cdot c^2 - 197}{1536\cdot s^{10}\cdot(6\cdot c^2 - 1)} =$	-0.0025	-

$$A_{55} = -\frac{2880\cdot c^{10} - 72480\cdot c^8 + 324000\cdot c^6 - 432000\cdot c^4 + 163470\cdot c^2 - 16245}{61440\cdot s^{11}\cdot(6\cdot c^2 - 1)\cdot(8\cdot c^4 - 11\cdot c^2 + 3)} =$$ -0.0003 -

B22 $$B_{22} = \frac{(2\cdot c^2 + 1)\cdot c}{4\cdot s^3} =$$ 1.1556 -

B24 $$B_{24} = \frac{c\cdot(272\cdot c^8 - 504\cdot c^6 - 192\cdot c^4 + 322\cdot c^2 + 21)}{384\cdot s^9} =$$ 1.5737 -

B33 $$B_{33} = \frac{3\cdot(8\cdot c^6 + 1)}{64\cdot s^6} =$$ 1.4457 -

$$B_{35} = \frac{88128\cdot c^{14} - 208224\cdot c^{12} + 70848\cdot c^{10} + 54000\cdot c^8 - 21816\cdot c^6 + 6264\cdot c^4 - 54\cdot c^2 - 81}{12288\cdot s^{12}\cdot(6\cdot c^2 - 1)} =$$
= 5.1727 -

B44 $$B_{44} = c\cdot\frac{768\cdot c^{10} - 488\cdot c^8 - 48\cdot c^6 + 48\cdot c^4 + 106\cdot c^2 - 21}{384\cdot s^9\cdot(6\cdot c^2 - 1)} =$$ 2.0428 -

$$B_{55} = \frac{192000\cdot c^{16} - 26720\cdot c^{14} + 83680\cdot c^{12} + 20160\cdot c^{10} - 7280\cdot c^8 + 7160\cdot c^6 - 1800\cdot c^4 - 1050\cdot c^2 + 225}{12288\cdot s^{10}\cdot(8\cdot c^4 - 11\cdot c^2 + 3)\cdot(6\cdot c^2 - 1)} =$$
= 3.3386 -

C1 $$C_1 = \frac{8\cdot c^4 - 8\cdot c^2 + 9}{8\cdot s^4} =$$ 1.9240 -

$$C_2 = \frac{3840\cdot c^{12} - 4096\cdot c^{10} + 2592\cdot c^8 - 1008\cdot c^6 + 5944\cdot c^4 - 1830\cdot c^2 + 147}{512\cdot s^{10}\cdot(6\cdot c^2 - 1)} =$$ 8.9142 -

C3 $$C_3 = -\frac{1}{4\cdot c\cdot s} =$$ -0.1129 -

C4 $$C_4 = \frac{12\cdot c^8 + 36\cdot c^6 - 162\cdot c^4 + 141\cdot c^2 - 27}{192\cdot c\cdot s^9} =$$ 0.1419 -

K1 $$K_1 = \lambda\cdot A_{11} + \lambda^3\cdot A_{13} + \lambda^5\cdot A_{15} =$$ 0.1552 -

K2	$K_2 = \lambda^2 \cdot A_{22} + \lambda^4 \cdot A_{24} =$	0.0065	-
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	-

Project	**:**	**N05-A Pipeline design**
Project #	**:**	19018
Subject	**:**	Buckling and Collapse
File #	**:**	19018-60-CAL-01003-02-01 - Buckling & Collapse calculations - 26m - installation flooded.xlsx
Client	**:**	ONE-Dyas
Client File #	**:**	

Originator	: EvW	Checked	:
Date	: 24/01/2020		
Revision	: 01		

Horizontal wave particle velocities

Water depth at which data required, z (w.r.t. seabed) 0.5080 m

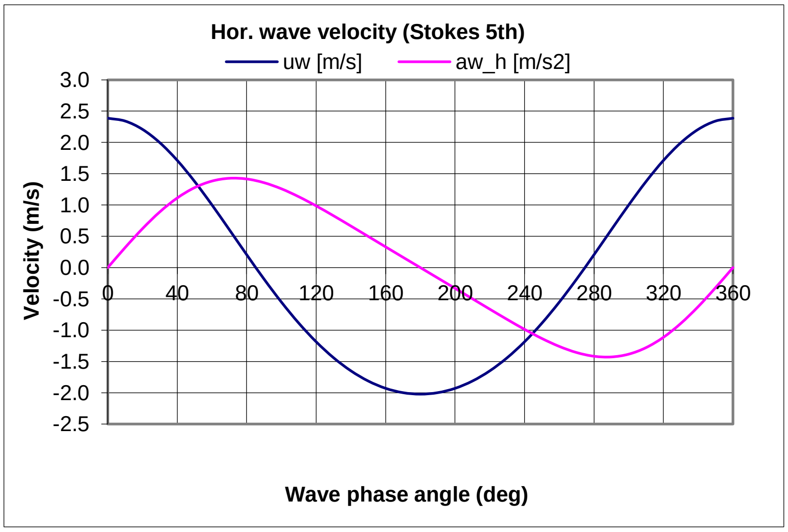
Horizontal velocity, u_w

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

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	2.3878	0.0000
10.00	2.3427	0.3202
20.00	2.2098	0.6227
30.00	1.9965	0.8913
40.00	1.7141	1.1129
50.00	1.3773	1.2783
60.00	1.0025	1.3832
70.00	0.6068	1.4278
80.00	0.2066	1.4167
90.00	-0.1836	1.3575
100.00	-0.5515	1.2596
110.00	-0.8877	1.1329
120.00	-1.1853	0.9867
130.00	-1.4402	0.8286
140.00	-1.6498	0.6646
150.00	-1.8129	0.4982
160.00	-1.9293	0.3316
170.00	-1.9990	0.1655
180.00	-2.0222	0.0000
190.00	-1.9990	-0.1655
200.00	-1.9293	-0.3316



210.00	-1.8129	-0.4982
220.00	-1.6498	-0.6646
230.00	-1.4402	-0.8286
240.00	-1.1853	-0.9867
250.00	-0.8877	-1.1329
260.00	-0.5515	-1.2596
270.00	-0.1836	-1.3575
280.00	0.2066	-1.4167
290.00	0.6068	-1.4278
300.00	1.0025	-1.3832
310.00	1.3773	-1.2783
320.00	1.7141	-1.1129
330.00	1.9965	-0.8913
340.00	2.2098	-0.6227
350.00	2.3427	-0.3202
360.00	2.3878	0.0000

U_{wm} = max. wave particle velocity = 2.39 m/s

Originator	: EvW	Checked	:
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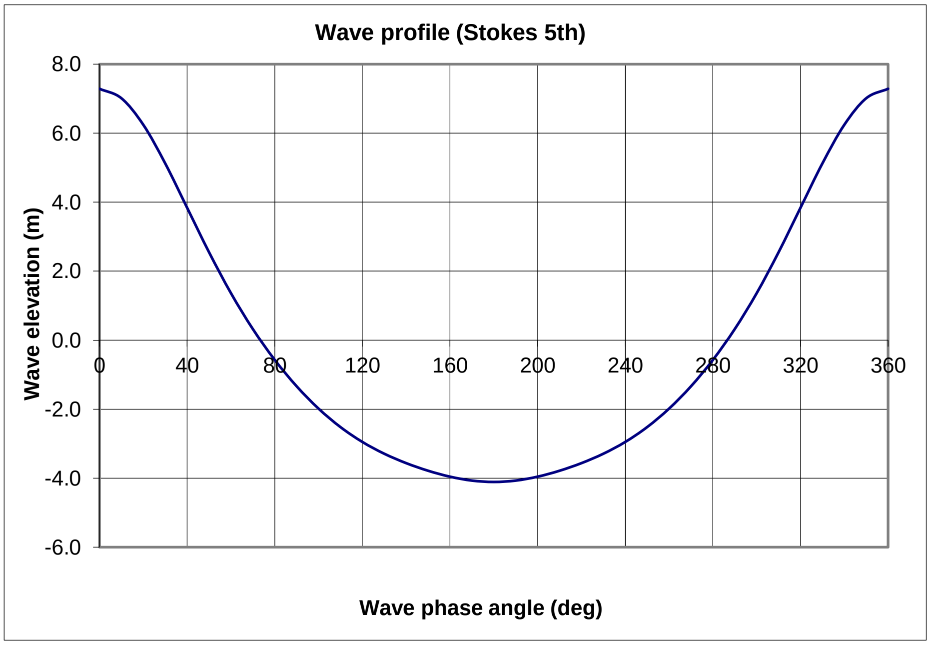
Wave profile h(t)

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

ϕ (deg.)	η(t) (m)
0.00	7.2865
10.00	7.0115
20.00	6.2418
30.00	5.1225
40.00	3.8366
50.00	2.5478
60.00	1.3619
70.00	0.3219
80.00	-0.5728
90.00	-1.3376
100.00	-1.9847
110.00	-2.5198
120.00	-2.9504
130.00	-3.2916
140.00	-3.5642
150.00	-3.7849
160.00	-3.9567
170.00	-4.0697
180.00	-4.1095
190.00	-4.0697
200.00	-3.9567
210.00	-3.7849
220.00	-3.5642
230.00	-3.2916
240.00	-2.9504
250.00	-2.5198
260.00	-1.9847
270.00	-1.3376
280.00	-0.5728
290.00	0.3219
300.00	1.3619
310.00	2.5478
320.00	3.8366
330.00	5.1225
340.00	6.2418
350.00	7.0115
360.00	7.2865



Project	**:**	**N05-A Pipeline design**
Project #	**:**	19018
Subject	**:**	Buckling and Collapse
File #	**:**	19018-60-CAL-01003-03-01 - Buckling & Collapse calculations - 26m - hydrotest.xlsx
Client	**:**	ONE-Dyas
Client File #	**:**	19018-60-CAL-01003-03-01 - Buckling & Collapse calculations - 26m - hydrotest.xlsx

Originator	: EvW	Checked	:
Date	: 24/01/2020		
Revision	: 01		

Buckling and Collapse - 20in x 20.62mm - 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)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm

Piggyback

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

Coating data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

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		96.1	kg/m^3
Pipeline content density used for this case:	Hydrotest	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	$W_{pl,a}$	=	4195.8	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	$F_{B,pl}$	=	2086.5	N/m
Buoyancy force piggyback	$F_{B,pb}$	=	0.0	N/m
Submerged pipeline weight,empty	$W_{pl,s,e}$	=	388.8	N/m
Submerged piggyback weight	$W_{pg,s}$	=	0.0	N/m
Total submerged bundle weight,empty	$W_{T,s,e}$	=	388.8	N/m
Total submerged bundle weight,water filled	$W_{T,s,f}$	=	2109.4	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}	=	29.68	m LAT
Minimum water depth		WD_{min}	=	26	m LAT
Other water depth (to be used for calculations)		WD	=	26	m LAT
Storm surge, RP1 yr		ss_{1yr}	=	-1.02	m LAT
Storm surge, RP100 yr		ss_{100yr}	=	-1.79	m LAT
Storm surge water level	SSWL = WD + ss	SSWL	=	24.98	m LAT
Highest Astronomical Tide		HAT	=	2.72	m

Waves (H_{max} & T_{max}):

Maximum wave height, RP1 yr - installation/hydrotes	$H_{max,1}$	=	11.4	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$	=	10.1	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$	=	16.9	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$	=	11.5	s

Project	**:**	**N05-A Pipeline design**
Project #	**:**	19018
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Client	**:**	ONE-Dyas
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Originator	: EvW	Checked	:
Date	: 24/01/2020		
Revision	: 01		

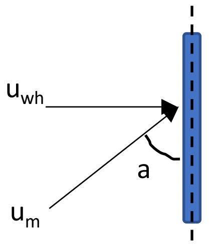
Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$\frac{H_{max}}{g \cdot T_z^2} =$ 0.0114

$\frac{SWL}{g \cdot T_z^2} =$ 0.0250

Wave theory selected:

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



Maximum wave particle velocity	u_{wm} =	2.39	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	2.39	m/s

Current:

Height above seabed at which velocity is known	z^* =	2	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.74	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.84	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	0.96	m/s
Current velocity at reference height	U_{czr} =	0.74	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} =	0.53	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 1822 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):	$P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3$ =	34.0	N/mm²
External plastic pipe collapse pressure (P_p)	$P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$ =	29.2	N/mm²
External implosion pipe collapse pressure (P_c):	P_c =	16.0	N/mm²
Maximum water column above mudline (WC_{max})	$WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT$ =	40.85	m
		0.4085	N/mm²
Actual external pressure (P_L)	$WC_{max} + SC_{pres}$ =	0.42	N/mm²

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) $M_c = D_g^2 d_n R_e$ = 1.8E+09 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 ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm

= 1.256E+06 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 = 13.6 -

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm

= 9.994E+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	=	2109	N/m
$F_D + F_I$	=	1822	N/m
g_w	=	1.1	-
g_h	=	1.2	-

Table 3 - NEN3656

q = 3188 N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 9.99E+05 N·m

Maximum span length, L_{max} = 56.0 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/mm^2

R_{ed} = 360.00 N/mm^2

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

s_p = 219.6 N/mm^2

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

Assessment: 0.0001 < 0.0028 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 23.9 **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 = 1.46E+06 N

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

Stokes 5th order wave theory

Water depth	WD =	26	m (LAT)
Storm surge	ss =	-1.02	m
Storm surge water level	$SWL = WD + ss$ =	24.98	m
Wave height	H =	11.4	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

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

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

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

Estimate actual wave length, L **143.093** **m**

$A = SWL/L_O$ = 0.1568

$B = \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right)$ = 0.1395

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

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

$D = (C_1 \cdot B)^2 - 4 \cdot (C_2 \cdot B) \cdot (-(A - B))$ = 0.1581

	-	eq. (I)	eq. (II)
λ1	0.228	0.0005	0.0000
λ2	Numerator of X < 0		
λ3	-0.228	2.8669	0.0000
λ4	Numerator of X < 0		

Item	Formula	Value	Unit
s	$s = \sinh\left(\frac{2\cdot\pi\cdot WL}{L}\right) =$	1.3304	-
c	$c = \cosh\left(\frac{2\cdot\pi\cdot WL}{L}\right) =$	1.6643	-
A11	$A_{11} = \frac{1}{s} =$	0.7516	-
A13	$A_{13} = \frac{-c^2\cdot(5\cdot c^2+1)}{8\cdot s^5} =$	-1.2336	-
	$A_{15} = -\frac{1184\cdot c^{10} - 1440\cdot c^8 - 1992\cdot c^6 + 2641\cdot c^4 - 249\cdot c^2 + 18}{1536\cdot s^{11}} =$	-2.4101	-
A22	$A_{22} = \frac{3}{8\cdot s^4} =$	0.1197	-
A24	$A_{24} = \frac{192\cdot c^8 - 424\cdot c^6 - 312\cdot c^4 + 480\cdot c^2 - 17}{768\cdot s^{10}} =$	0.0907	-
A33	$A_{33} = \frac{13 - 4\cdot c^2}{64\cdot s^7} =$	0.0041	-
	$A_{35} = \frac{512\cdot c^{12} + 4224\cdot c^{10} - 6800\cdot c^8 - 12808\cdot c^6 + 16704\cdot c^4 - 3154\cdot c^2 - 107}{4096\cdot s^{13}\cdot(6\cdot c^2 - 1)} =$	0.1402	-
A44	$A_{44} = \frac{80\cdot c^6 - 816\cdot c^4 + 1338\cdot c^2 - 197}{1536\cdot s^{10}\cdot(6\cdot c^2 - 1)} =$	-0.0025	-

$$A_{55} = -\frac{2880\cdot c^{10} - 72480\cdot c^{8} + 324000\cdot c^{6} - 432000\cdot c^{4} + 163470\cdot c^{2} - 16245}{61440\cdot s^{11}\cdot(6\cdot c^{2}-1)\cdot(8\cdot c^{4}-11\cdot c^{2}+3)} =$$ -0.0003 -

B22 $$B_{22} = \frac{(2\cdot c^{2}+1)\cdot c}{4\cdot s^{3}} =$$ 1.1556 -

B24 $$B_{24} = \frac{c\cdot(272\cdot c^{8} - 504\cdot c^{6} - 192\cdot c^{4} + 322\cdot c^{2} + 21)}{384\cdot s^{9}} =$$ 1.5737 -

B33 $$B_{33} = \frac{3\cdot(8\cdot c^{6}+1)}{64\cdot s^{6}} =$$ 1.4457 -

$$B_{35} = \frac{88128\cdot c^{14} - 208224\cdot c^{12} + 70848\cdot c^{10} + 54000\cdot c^{8} - 21816\cdot c^{6} + 6264\cdot c^{4} - 54\cdot c^{2} - 81}{12288\cdot s^{12}\cdot(6\cdot c^{2}-1)} =$$ = 5.1727 -

B44 $$B_{44} = c\cdot\frac{768\cdot c^{10} - 488\cdot c^{8} - 48\cdot c^{6} + 48\cdot c^{4} + 106\cdot c^{2} - 21}{384\cdot s^{9}\cdot(6\cdot c^{2}-1)} =$$ 2.0428 -

$$B_{55} = \frac{192000\cdot c^{16} - 26720\cdot c^{14} + 83680\cdot c^{12} + 20160\cdot c^{10} - 7280\cdot c^{8} + 7160\cdot c^{6} - 1800\cdot c^{4} - 1050\cdot c^{2} + 225}{12288\cdot s^{10}\cdot(8\cdot c^{4}-11\cdot c^{2}+3)\cdot(6\cdot c^{2}-1)} =$$ = 3.3386 -

C1 $$C_{1} = \frac{8\cdot c^{4} - 8\cdot c^{2} + 9}{8\cdot s^{4}} =$$ 1.9240 -

$$C_{2} = \frac{3840\cdot c^{12} - 4096\cdot c^{10} + 2592\cdot c^{8} - 1008\cdot c^{6} + 5944\cdot c^{4} - 1830\cdot c^{2} + 147}{512\cdot s^{10}\cdot(6\cdot c^{2}-1)} =$$ 8.9142 -

C3 $$C_{3} = -\frac{1}{4\cdot c\cdot s} =$$ -0.1129 -

C4 $$C_{4} = \frac{12\cdot c^{8} + 36\cdot c^{6} - 162\cdot c^{4} + 141\cdot c^{2} - 27}{192\cdot c\cdot s^{9}} =$$ 0.1419 -

K1 $$K_{1} = \lambda\cdot A_{11} + \lambda^{3}\cdot A_{13} + \lambda^{5}\cdot A_{15} =$$ 0.1552 -

K2	$K_2 = \lambda^2 \cdot A_{22} + \lambda^4 \cdot A_{24} =$	0.0065	-
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	-

Project : **N05-A Pipeline design**
Project # : 19018
Subject : Buckling and Collapse
File # : 19018-60-CAL-01003-03-01 - Buckling & Collapse calculations - 26m - hydrotest.xlsx

Client : ONE-Dyas
Client File # :

Originator	: EvW	Checked	:
Date	: 24/01/2020		
Revision	: 01		

Horizontal wave particle velocities

Water depth at which data required, z (w.r.t. seabed) 0.5080 m

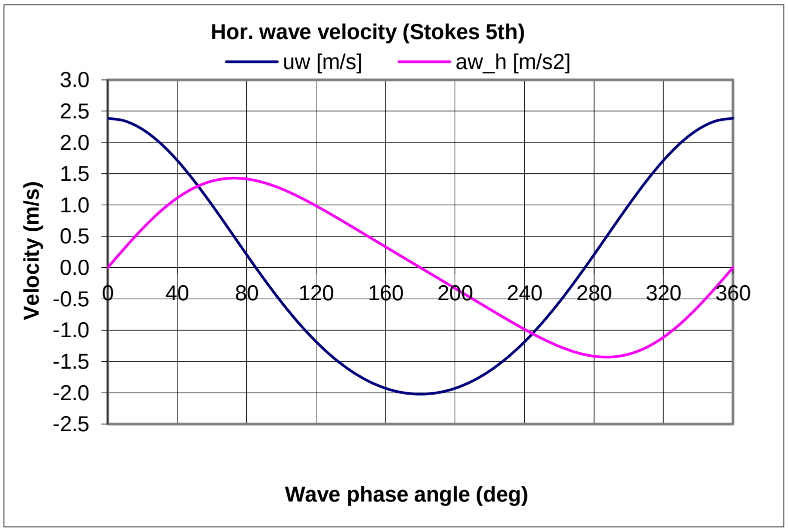
Horizontal velocity, u_w

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

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	2.3878	0.0000
10.00	2.3427	0.3202
20.00	2.2098	0.6227
30.00	1.9965	0.8913
40.00	1.7141	1.1129
50.00	1.3773	1.2783
60.00	1.0025	1.3832
70.00	0.6068	1.4278
80.00	0.2066	1.4167
90.00	-0.1836	1.3575
100.00	-0.5515	1.2596
110.00	-0.8877	1.1329
120.00	-1.1853	0.9867
130.00	-1.4402	0.8286
140.00	-1.6498	0.6646
150.00	-1.8129	0.4982
160.00	-1.9293	0.3316
170.00	-1.9990	0.1655
180.00	-2.0222	0.0000
190.00	-1.9990	-0.1655
200.00	-1.9293	-0.3316



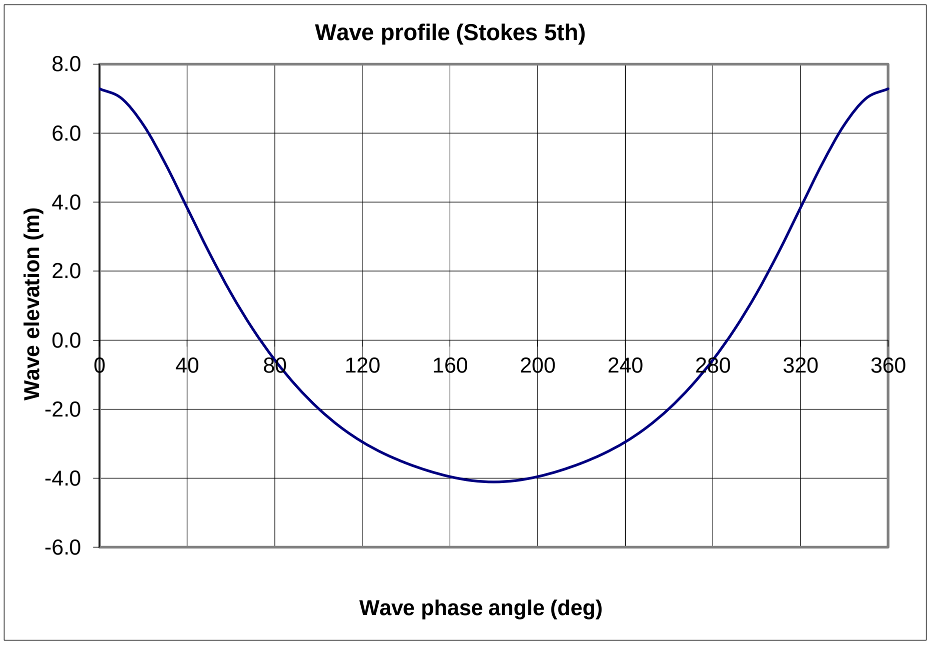
210.00	-1.8129	-0.4982
220.00	-1.6498	-0.6646
230.00	-1.4402	-0.8286
240.00	-1.1853	-0.9867
250.00	-0.8877	-1.1329
260.00	-0.5515	-1.2596
270.00	-0.1836	-1.3575
280.00	0.2066	-1.4167
290.00	0.6068	-1.4278
300.00	1.0025	-1.3832
310.00	1.3773	-1.2783
320.00	1.7141	-1.1129
330.00	1.9965	-0.8913
340.00	2.2098	-0.6227
350.00	2.3427	-0.3202
360.00	2.3878	0.0000

U_{wm} = max. wave particle velocity = 2.39 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	7.2865
10.00	7.0115
20.00	6.2418
30.00	5.1225
40.00	3.8366
50.00	2.5478
60.00	1.3619
70.00	0.3219
80.00	-0.5728
90.00	-1.3376
100.00	-1.9847
110.00	-2.5198
120.00	-2.9504
130.00	-3.2916
140.00	-3.5642
150.00	-3.7849
160.00	-3.9567
170.00	-4.0697
180.00	-4.1095
190.00	-4.0697
200.00	-3.9567
210.00	-3.7849
220.00	-3.5642
230.00	-3.2916
240.00	-2.9504
250.00	-2.5198
260.00	-1.9847
270.00	-1.3376
280.00	-0.5728
290.00	0.3219
300.00	1.3619
310.00	2.5478
320.00	3.8366
330.00	5.1225
340.00	6.2418
350.00	7.0115
360.00	7.2865



Project	**:**	**N05-A Pipeline design**
Project #	**:**	19018
Subject	**:**	Buckling and Collapse
File #	**:**	19018-60-CAL-01003-04-01 - Buckling & Collapse calculations - 8m - operation.xlsx
Client	**:**	ONE-Dyas
Client File #	**:**	19018-60-CAL-01003-04-01 - Buckling & Collapse calculations - 8m - operation.xlsx

Originator	: EvW	Checked	:
Date	: 27/01/2020		
Revision	: 01		

Buckling and Collapse - 20in x 20.62mm - Operational

Situation

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

4
Operational

	Pressure (barg)	Temperature (deg. C)
Installation (P_{in}, T_{in})	2	15
Design (P_d, T_d)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm
Piggyback				
Nominal diameter		$OD_{nom,p}$ =	0	mm
Nominal wall thickness		$d_{nom,p}$ =	0.0	mm

Coating data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Material		=	L360NB	
Design temperature	T_d	=	50	°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		96.1	kg/m^3
Pipeline content density used for this case:	Operational	96.1	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	$W_{pl,a}$	=	2636.6	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	$F_{B,pl}$	=	2086.5	N/m
Buoyancy force piggyback	$F_{B,pb}$	=	0.0	N/m
Submerged pipeline weight,empty	$W_{pl,s,e}$	=	388.8	N/m
Submerged piggyback weight	$W_{pg,s}$	=	0.0	N/m
Total submerged bundle weight,empty	$W_{T,s,e}$	=	388.8	N/m
Total submerged bundle weight,water filled	$W_{T,s,f}$	=	2109.4	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}	=	11.5	m LAT
Minimum water depth		WD_{min}	=	8	m LAT
Other water depth (to be used for calculations)		WD	=	8	m LAT
Storm surge, RP1 yr		ss_{1yr}	=	-0.14	m LAT
Storm surge, RP100 yr		ss_{100yr}	=	-0.78	m LAT
Storm surge water level	SSWL = WD + ss	SSWL	=	7.22	m LAT
Highest Astronomical Tide		HAT	=	3.5	m

Waves (H_{max} & T_{max}):

Maximum wave height, RP1 yr - installation/hydrotes	$H_{max,1}$	=	5.2	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$	=	7.7	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$	=	6.2	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$	=	8.1	s

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

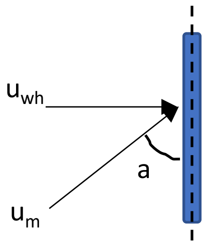
$\frac{H_{max}}{g \cdot T_z^2} =$ 0.0096

$\frac{SWL}{g \cdot T_z^2} =$ 0.0112

Wave theory selected:
1. Airy/linear wave; 2. Stokes 5th

Wave particle velocity from metocean data

Maximum wave particle velocity	u_{wm} =	1.60	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	1.60	m/s



Current:

Height above seabed at which velocity is known	z* =	1	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.89	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	1	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	1.12	m/s
Current velocity at reference height	U_{czr} =	1.12	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} =	0.89	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 1372 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): $P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3$ = 34.0 N/mm^2

External plastic pipe collapse pressure (P_p) $P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$ = 29.2 N/mm^2

External implosion pipe collapse pressure (P_c): P_c = 16.0 N/mm^2

Maximum water column above mudline (WC_{max}) $WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT$ = 18.1 m
0.181 N/mm^2

Actual external pressure (P_L) $WC_{max} + SC_{pres}$ = 0.19 N/mm^2

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

Table 4 - NEN3656

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

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

Collapse - bending moment only (K.3.3.5.2)

Buckling bending moment (M_c) $M_c = D_g^2 d_n R_e$ = 1.8E+09 N·mm

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

Table 4 - NEN3656

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

Maximum allowable bending moment ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm
= 1.256E+06 N·m

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

Assessment: $\frac{\gamma_{g,p} \times P_L}{P_c / \gamma_{m,p}} + \left(\frac{\gamma_{g,M} \times M_L}{M_c / \gamma_{m,M}} \right)^n \leq \gamma_M$ **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 = 13.6 -

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm
= 1.001E+06 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 = 389 N/m
$F_D + F_I$ = 1372 N/m

g_w =	1.1	-
g_h =	1.2	-

Table 3 - NEN3656

q = 1700 N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.00E+06 N·m

Maximum span length, L_{max} = 76.7 m

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 = 46 -

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 = 169.3 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: 0.0005 < 0.0030 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 23.9 **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 = -2.05E+06 N

$L_{max,bb}$ = 61.7 m

Project	**: N05-A Pipeline design**
Project #	: 19018
Subject	: Buckling and Collapse
File #	: 19018-60-CAL-01003-05-01 - Buckling & Collapse calculations - 8m - installation flooded.xlsx
Client	: ONE-Dyas
Client File #	: 19018-60-CAL-01003-05-01 - Buckling & Collapse calculations - 8m - installation flooded.xlsx

Originator	: EvW	Checked	:
Date	: 27/01/2020		
Revision	: 01		

Buckling and Collapse - 20in x 20.62mm - 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)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm

Piggyback

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

Coating data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

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		96.1	kg/m^3
Pipeline content density used for this case:	Installation: filled	1025	kg/m^3

Pipeline Weights

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

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

Pipeline weight in air	$W_{pl,a}$	=	4195.8	N/m
Piggyback weight in air	$W_{pg,a}$	=	0.0	N/m
Buoyancy force pipeline	$F_{B,pl}$	=	2086.5	N/m
Buoyancy force piggyback	$F_{B,pb}$	=	0.0	N/m
Submerged pipeline weight,empty	$W_{pl,s,e}$	=	388.8	N/m
Submerged piggyback weight	$W_{pg,s}$	=	0.0	N/m
Total submerged bundle weight,empty	$W_{T,s,e}$	=	388.8	N/m
Total submerged bundle weight,water filled	$W_{T,s,f}$	=	2109.4	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}	=	11.5	m LAT
Minimum water depth		WD_{min}	=	8	m LAT
Other water depth (to be used for calculations)		WD	=	8	m LAT
Storm surge, RP1 yr		ss_{1yr}	=	-0.14	m LAT
Storm surge, RP100 yr		ss_{100yr}	=	-0.78	m LAT
Storm surge water level	SSWL = WD + ss	SSWL	=	7.86	m LAT
Highest Astronomical Tide		HAT	=	3.5	m

Waves (H_{max} & T_{max}):

Maximum wave height, RP1 yr - installation/hydrotes	$H_{max,1}$	=	5.2	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$	=	7.7	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$	=	6.2	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$	=	8.1	s

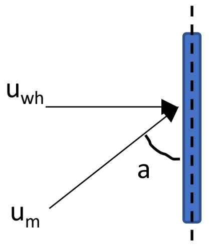
Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$\frac{H_{max}}{g \cdot T_z^2} =$ 0.0089

$\frac{SWL}{g \cdot T_z^2} =$ 0.0135

Wave theory selected:

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



	Wave particle velocity from metocean data		
Maximum wave particle velocity	u_{wm} =	1.30	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	1.30	m/s

Current:

Height above seabed at which velocity is known	z^* =	1	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.89	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	1	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	1.12	m/s
Current velocity at reference height	U_{czr} =	0.89	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} =	0.71	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 891 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):	$P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3$ =	34.0	N/mm²
External plastic pipe collapse pressure (P_p)	$P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$ =	29.2	N/mm²
External implosion pipe collapse pressure (P_c):	P_c =	16.0	N/mm²
Maximum water column above mudline (WC_{max})	$WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT$ =	18.1	m
		0.181	N/mm²
Actual external pressure (P_L)	$WC_{max} + SC_{pres}$ =	0.19	N/mm²

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

Table 4 - NEN3656

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

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

Collapse - bending moment only (K.3.3.5.2)

Buckling bending moment (M_c) $M_c = D_g^2 d_n R_e$ = 1.8E+09 N·mm

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

Table 4 - NEN3656

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

Maximum allowable bending moment ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm
= 1.256E+06 N·m

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

Assessment: $\frac{\gamma_{g,p} \times P_L}{P_c / \gamma_{m,p}} + \left(\frac{\gamma_{g,M} \times M_L}{M_c / \gamma_{m,M}} \right)^n \leq \gamma_M$ **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 =	13.6	-

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm
= 1.001E+06 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 =	2109	N/m
$F_D + F_I$ =	891	N/m
g_w =	1.1	-
g_h =	1.2	-

Table 3 - NEN3656

q = 2555 N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.00E+06 N·m

Maximum span length, L_{max} =	62.6	m

Project	**:**	**N05-A Pipeline design**
Project #	**:**	19018
Subject	**:**	Buckling and Collapse
File #	**:**	19018-60-CAL-01003-05-01 - Buckling & Collapse calculations - 8m - installation flooded.xlsx
Client	**:**	ONE-Dyas
Client File #	**:**	19018-60-CAL-01003-05-01 - Buckling & Collapse calculations - 8m - installation flooded.xlsx

Originator	: EvW	Checked :
Date	: 27/01/2020	
Revision	: 01	

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

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

s_p = 3.1 N/mm²

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

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 = 23.9 **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 =	-8.97E+05	N

$L_{max,bb}$ = 93.1 m

Buckling and Collapse - 20in x 20.62mm - 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)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

	Formula	Symbol	Value	Unit
Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm

Piggyback

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

Coating data

		Value	Unit
Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

		Value	Unit
gravitational acceleration	g =	9.81	m/s^2

Originator	: EvW	Checked	:
Date	: 27/01/2020		
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				96.1	kg/m^3
Pipeline content density used for this case:	Hydrotest			1025	kg/m^3
Pipeline Weights					
Pipeline weight in air	$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$	$W_{pl,a}$	=	4195.8	N/m
Piggyback weight in air		$W_{pg,a}$	=	0.0	N/m
Buoyancy force pipeline	$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$	$F_{B,pl}$	=	2086.5	N/m
Buoyancy force piggyback		$F_{B,pb}$	=	0.0	N/m
Submerged pipeline weight,empty		$W_{pl,s,e}$	=	388.8	N/m
Submerged piggyback weight		$W_{pg,s}$	=	0.0	N/m
Total submerged bundle weight,empty		$W_{T,s,e}$	=	388.8	N/m
Total submerged bundle weight,water filled		$W_{T,s,f}$	=	2109.4	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}	=	11.5	m LAT
Minimum water depth		WD_{min}	=	8	m LAT
Other water depth (to be used for calculations)		WD	=	8	m LAT
Storm surge, RP1 yr		ss_{1yr}	=	-0.14	m LAT
Storm surge, RP100 yr		ss_{100yr}	=	-0.78	m LAT
Storm surge water level	SSWL = WD + ss	SSWL	=	7.86	m LAT
Highest Astronomical Tide		HAT	=	3.5	m
Waves (H_{max} & T_{max}):					
Maximum wave height, RP1 yr - installation/hydrotes		$H_{max,1}$	=	5.2	m
Associated maximum wave period, RP1 yr		$T_{ass,1}$	=	7.7	s
Maximum wave height, RP100 yr - operational		$H_{max,100}$	=	6.2	m
Associated maximum wave period, RP100 yr		$T_{ass,100}$	=	8.1	s

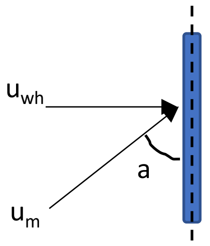
Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$\frac{H_{max}}{g \cdot T_z^2} =$ 0.0089

$\frac{SWL}{g \cdot T_z^2} =$ 0.0135

Wave theory selected:

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



Wave particle velocity from metocean data

Maximum wave particle velocity	u_{wm} =	1.30	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	1.30	m/s

Current:

Height above seabed at which velocity is known	z* =	1	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.89	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	1	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	1.12	m/s
Current velocity at reference height	U_{czr} =	0.89	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} =	0.71	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 891 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): $P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3 =$ 34.0 N/mm^2

External plastic pipe collapse pressure (P_p) $P_p = \frac{2 R_e d_{nom}}{OD_{nom}} =$ 29.2 N/mm^2

External implosion pipe collapse pressure (P_c): P_c = 16.0 N/mm^2

Maximum water column above mudline (WC_{max}) $WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT =$ 18.1 m

0.181 N/mm^2

Actual external pressure (P_L) $WC_{max} + SC_{pres} =$ 0.19 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) $M_c = D_g^2 d_n R_e$ = 1.8E+09 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 ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm
= 1.256E+06 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 = 13.6 -

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm
= 1.001E+06 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 =	2109	N/m
$F_D + F_I$ =	891	N/m
g_w =	1.1	-
g_h =	1.2	-

Table 3 - NEN3656

q = 2555 N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.00E+06 N·m

Maximum span length,	L_{max} =	62.6 m

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 = 219.6 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 < 0.0028 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 23.9 **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	=	1.46E+06	N

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

Project	**:**	**N05-A Pipeline design**
Project #	**:**	19018
Subject	**:**	Buckling and Collapse
File #	**:**	19018-60-CAL-01003-07-01 - Buckling & Collapse calculations - 17m - operation.xlsx
Client	**:**	ONE-Dyas
Client File #	**:**	19018-60-CAL-01003-07-01 - Buckling & Collapse calculations - 17m - operation.xlsx

Originator	: EvW	Checked	:
Date	: 27/01/2020		
Revision	: 01		

Buckling and Collapse - 20in x 20.62mm - 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)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm

Piggyback

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

Coating data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Material		=	L360NB	
Design temperature	T_d	=	50	°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			96.1	kg/m^3
Pipeline content density used for this case:	Operational		96.1	kg/m^3

Pipeline Weights

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

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

Pipeline weight in air	$W_{pl,a}$	=	2636.6	N/m
Piggyback weight in air	$W_{pg,a}$	=	0.0	N/m
Buoyancy force pipeline	$F_{B,pl}$	=	2086.5	N/m
Buoyancy force piggyback	$F_{B,pb}$	=	0.0	N/m
Submerged pipeline weight,empty	$W_{pl,s,e}$	=	388.8	N/m
Submerged piggyback weight	$W_{pg,s}$	=	0.0	N/m
Total submerged bundle weight,empty	$W_{T,s,e}$	=	388.8	N/m
Total submerged bundle weight,water filled	$W_{T,s,f}$	=	2109.4	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}	=	20.6	m LAT
Minimum water depth		WD_{min}	=	17	m LAT
Other water depth (to be used for calculations)		WD	=	17	m LAT
Storm surge, RP1 yr		ss_{1yr}	=	-0.58	m LAT
Storm surge, RP100 yr		ss_{100yr}	=	-1.29	m LAT
Storm surge water level	SSWL = WD + ss	SSWL	=	15.72	m LAT
Highest Astronomical Tide		HAT	=	3.11	m

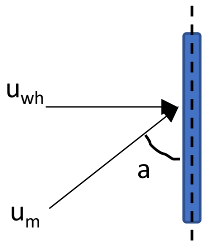
Waves (H_{max} & T_{max}):

Maximum wave height, RP1 yr - installation/hydrotes	$H_{max,1}$	=	8.3	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$	=	8.9	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$	=	11.55	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$	=	9.8	s

Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures") $\frac{H_{max}}{g \cdot T_z^2} =$ 0.0123

$\frac{SWL}{g \cdot T_z^2} =$ 0.0167

Wave theory selected:
1. Airy/linear wave; 2. Stokes 5th



Wave particle velocity from interpolated data

Maximum wave particle velocity	u_{wm} =	2.80	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	2.80	m/s

Current:

Height above seabed at which velocity is known	z^* =	1	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.82	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.92	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	1.04	m/s
Current velocity at reference height	U_{czr} =	1.04	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} =	0.83	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 2909 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): $P_e = \frac{2E_s}{1-\nu^2}(\frac{d_{nom}}{OD_{av}})^3$ = 34.0 N/mm^2

External plastic pipe collapse pressure (P_p) $P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$ = 29.2 N/mm^2

External implosion pipe collapse pressure (P_c): P_c = 16.0 N/mm^2

Maximum water column above mudline (WC_{max}) $WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT$ = 29.485 m
0.29485 N/mm^2

Actual external pressure (P_L) $WC_{max} + SC_{pres}$ = 0.30 N/mm^2

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

Table 4 - NEN3656

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

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

Collapse - bending moment only (K.3.3.5.2)

Buckling bending moment (M_c) $M_c = D_g^2 d_n R_e$ = 1.8E+09 N·mm

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

Table 4 - NEN3656

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

Maximum allowable bending moment ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm
= 1.256E+06 N·m

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

Assessment: $\frac{\gamma_{g,p} \times P_L}{P_c / \gamma_{m,p}} + \left(\frac{\gamma_{g,M} \times M_L}{M_c / \gamma_{m,M}} \right)^n \leq \gamma_M$ **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 =	13.6	-

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm
= 1.000E+06 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 =	389	N/m
$F_D + F_I$ =	2909	N/m
g_w =	1.1	-
g_h =	1.2	-
Table 3 - NEN3656		
q =	3517	N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.00E+06 N·m

Maximum span length, L_{max} = 53.3 m

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 =	46	-
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 =	169.3	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: 0.0005 < 0.0030 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 23.9 **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 =	-2.05E+06	N
$L_{max,bb}$ =	**61.7**	**m**

Project	**: N05-A Pipeline design**
Project #	: 19018
Subject	: Buckling and Collapse
File #	: 19018-60-CAL-01003-08-01 - Buckling & Collapse calculations - 17m - installation flooded.xlsx
Client	: ONE-Dyas
Client File #	: 19018-60-CAL-01003-08-01 - Buckling & Collapse calculations - 17m - installation flooded.xlsx

Originator	: EvW	Checked	:
Date	: 27/01/2020		
Revision	: 01		

Buckling and Collapse - 20in x 20.62mm - 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)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm

Piggyback

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

Coating data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

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			96.1	kg/m^3
Pipeline content density used for this case:	Installation: filled		1025	kg/m^3
Pipeline Weights				
Pipeline weight in air	$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$	$W_{pl,a}$ =	4195.8	N/m
Piggyback weight in air		$W_{pg,a}$ =	0.0	N/m
Buoyancy force pipeline	$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$	$F_{B,pl}$ =	2086.5	N/m
Buoyancy force piggyback		$F_{B,pb}$ =	0.0	N/m
Submerged pipeline weight,empty		$W_{pl,s,e}$ =	388.8	N/m
Submerged piggyback weight		$W_{pg,s}$ =	0.0	N/m
Total submerged bundle weight,empty		$W_{T,s,e}$ =	388.8	N/m
Total submerged bundle weight,water filled		$W_{T,s,f}$ =	2109.4	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} =	20.6	m LAT
Minimum water depth		WD_{min} =	17	m LAT
Other water depth (to be used for calculations)		WD =	17	m LAT
Storm surge, RP1 yr		ss_{1yr} =	-0.58	m LAT
Storm surge, RP100 yr		ss_{100yr} =	-1.29	m LAT
Storm surge water level	SSWL = WD + ss	SSWL =	16.42	m LAT
Highest Astronomical Tide		HAT =	3.11	m
Waves (H_{max} & T_{max}):				
Maximum wave height, RP1 yr - installation/hydrotes		$H_{max,1}$ =	8.3	m
Associated maximum wave period, RP1 yr		$T_{ass,1}$ =	8.9	s
Maximum wave height, RP100 yr - operational		$H_{max,100}$ =	11.55	m
Associated maximum wave period, RP100 yr		$T_{ass,100}$ =	9.8	s

enersea

Originator	: EvW	Checked	:
Date	: 27/01/2020		
Revision	: 01		

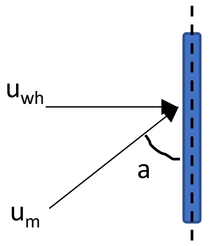
Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$\frac{H_{max}}{g \cdot T_z^2} =$ 0.0107

$\frac{SWL}{g \cdot T_z^2} =$ 0.0211

Wave theory selected:

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



Wave particle velocity from interpolated data

Maximum wave particle velocity	u_{wm} =	1.85	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	1.85	m/s

Current:

Height above seabed at which velocity is known	z^* =	1	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.82	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.92	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	1.04	m/s
Current velocity at reference height	U_{czr} =	0.82	m/s
Angle of attack relative to pipeline axis	α_{uc} =	90	deg
Horizontal current velocity ⊥ to P/L $\quad \frac{7}{8} \cdot U_{czr} \cdot \left(\frac{OD_{nom}}{z_r}\right)^{1/7} \cdot \sin(\alpha_{uc}) =$	u_{ch} =	0.65	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 1380 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): $P_e = \frac{2E_s}{1-\nu^2}\left(\frac{d_{nom}}{OD_{av}}\right)^3 =$ 34.0 N/mm^2

External plastic pipe collapse pressure (P_p) $P_p = \frac{2 R_e d_{nom}}{OD_{nom}} =$ 29.2 N/mm^2

External implosion pipe collapse pressure (P_c): $P_c =$ 16.0 N/mm^2

Maximum water column above mudline (WC_{max}) $WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT =$ 29.485 m

0.29485 N/mm^2

Actual external pressure (P_L) $WC_{max} + SC_{pres} =$ 0.30 N/mm^2

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

Table 4 - NEN3656

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

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

Collapse - bending moment only (K.3.3.5.2)

Buckling bending moment (M_c) $M_c = D_g^2 d_n R_e$ = 1.8E+09 N·mm

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

Table 4 - NEN3656

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

Maximum allowable bending moment ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm
= 1.256E+06 N·m

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

Assessment: $\frac{\gamma_{g,p} \times P_L}{P_c / \gamma_{m,p}} + \left(\frac{\gamma_{g,M} \times M_L}{M_c / \gamma_{m,M}} \right)^n \leq \gamma_M$ **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 = 13.6 -

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm
= 1.000E+06 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 = 2109 N/m
$F_D + F_I$ = 1380 N/m
g_w = 1.1 -
g_h = 1.2 -
Table 3 - NEN3656
q = 2851 N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.00E+06 N·m

Maximum span length, L_{max} = 59.2 m

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	=	3.1	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: 0.0001 < 0.0033 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 23.9 **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	=	-8.97E+05	N
$L_{max,bb}$	**=**	**93.1**	**m**

Project	**: N05-A Pipeline design**
Project #	: 19018
Subject	: Buckling and Collapse
File #	: 19018-60-CAL-01003-09-01 - Buckling & Collapse calculations - 17m - hydrotest.xlsx
Client	: ONE-Dyas
Client File #	: 19018-60-CAL-01003-09-01 - Buckling & Collapse calculations - 17m - hydrotest.xlsx

Originator	: EvW	Checked	:
Date	: 27/01/2020		
Revision	: 01		

Buckling and Collapse - 20in x 20.62mm - Hydrotest

Situation

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

3
Hydrotest

	Pressure (barg)	Temperature (deg. C)
Installation (P_{in}, T_{in})	2	15
Design (P_d, T_d)	111	50
Hydrotest (P_t, T_t)	144	15

Pipeline properties

Nominal diameter		OD_{nom} =	20	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Max. OD deviation	$OD_{max,dev} = 0.35 \cdot d_{min}$	$OD_{max,dev}$ =	7.22	mm
Min. OD deviation	$OD_{min,dev} = 0.35 \cdot d_{min}$	$OD_{min,dev}$ =	7.22	mm
Max. ovalised diameter	$OD_{max} = OD_{nom} + 0.35 \cdot dmin$	OD_{max} =	515.217	mm
Min. ovalised diameter	$OD_{min} = OD_{nom} - 0.35 \cdot dmin$	OD_{min} =	500.783	mm
Initial ovalisation	$\delta_0 = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}}$	d_0 =	0.014	-
Cross sectional area of steel		A =	31572	mm^2
Moment of Inertia		I =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm

Piggyback

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

Coating data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

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				96.1	kg/m^3
Pipeline content density used for this case:	Hydrotest			1025	kg/m^3
Pipeline Weights					
Pipeline weight in air	$W_{pipe} = \{A_s \cdot \rho_s + A_{coat} \cdot \rho_{coat} + A_{inside} \cdot \rho_{content}\} \cdot g$	$W_{pl,a}$	=	4195.8	N/m
Piggyback weight in air		$W_{pg,a}$	=	0.0	N/m
Buoyancy force pipeline	$F_b = \frac{\pi}{4} \cdot OD_{tot}^2 \cdot \rho_{seawater} \cdot g$	$F_{B,pl}$	=	2086.5	N/m
Buoyancy force piggyback		$F_{B,pb}$	=	0.0	N/m
Submerged pipeline weight,empty		$W_{pl,s,e}$	=	388.8	N/m
Submerged piggyback weight		$W_{pg,s}$	=	0.0	N/m
Total submerged bundle weight,empty		$W_{T,s,e}$	=	388.8	N/m
Total submerged bundle weight,water filled		$W_{T,s,f}$	=	2109.4	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}	=	20.6	m LAT
Minimum water depth		WD_{min}	=	17	m LAT
Other water depth (to be used for calculations)		WD	=	17	m LAT
Storm surge, RP1 yr		ss_{1yr}	=	-0.58	m LAT
Storm surge, RP100 yr		ss_{100yr}	=	-1.29	m LAT
Storm surge water level	SSWL = WD + ss	SSWL	=	16.42	m LAT
Highest Astronomical Tide		HAT	=	3.11	m
Waves (H_{max} & T_{max}):					
Maximum wave height, RP1 yr - installation/hydrotes		$H_{max,1}$	=	8.3	m
Associated maximum wave period, RP1 yr		$T_{ass,1}$	=	8.9	s
Maximum wave height, RP100 yr - operational		$H_{max,100}$	=	11.55	m
Associated maximum wave period, RP100 yr		$T_{ass,100}$	=	9.8	s

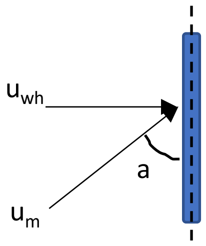
Applied wave theory (per fig. 6.36 "Dynamics of Fixed Marine Structures")

$\frac{H_{max}}{g \cdot T_z^2} =$ 0.0107

$\frac{SWL}{g \cdot T_z^2} =$ 0.0211

Wave theory selected:

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



Wave particle velocity from interpolated data

Maximum wave particle velocity	u_{wm} =	1.85	m/s
Angle of attack relative to pipeline axis	α_{uw} =	90	deg
Horizontal wave velocity ⊥ to P/L	u_{wh} =	1.85	m/s

Current:

Height above seabed at which velocity is known	z* =	1	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.82	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.92	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	1.04	m/s
Current velocity at reference height	U_{czr} =	0.82	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} =	0.65	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 1380 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): $P_e = \frac{2E_s}{1-\nu^2}(\frac{d_{nom}}{OD_{av}})^3$ = 34.0 N/mm²

External plastic pipe collapse pressure (P_p) $P_p = \frac{2 R_e d_{nom}}{OD_{nom}}$ = 29.2 N/mm²

External implosion pipe collapse pressure (P_c): P_c = 16.0 N/mm²

Maximum water column above mudline (WC_{max}) $WC_{max} = WD_{max} + 0.5 \cdot H_{max,100} + HAT$ = 29.485 m
0.29485 N/mm²

Actual external pressure (P_L) $WC_{max} + SC_{pres}$ = 0.30 N/mm²

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) $M_c = D_g^2 d_n R_e$ = 1.8E+09 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 ($M_{L,b}$) $M_{L,b}$ = 1.3E+09 N·mm
= 1.256E+06 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	-
$n = 1 + 300 \cdot d_{nom} / OD_g$ n =	13.6	-

Maximum allowable bending moment ($M_{L,pb}$) $M_{L,pb}$ = 1.0E+09 N·mm
= 1.000E+06 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 =	2109	N/m
$F_D + F_I$ =	1380	N/m
g_w =	1.1	-
g_h =	1.2	-
Table 3 - NEN3656		
q =	2851	N/m

Maximum allowable bending moment ($M_{L,m}$) is smallest of $M_{L,b}$ and $M_{L,pb}$ $M_{L,m}$ = 1.000E+06 N·m

Maximum span length, L_{max} = 59.2 m

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 = 219.6 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 < 0.0028 **OK**

Local buckling (K.3.3.3)

Assessment: $\frac{(OD_{nom} - d_{min})}{d_{nom}} < 55$: no check on local buckling required = 23.9 **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 = 1.46E+06 N

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

C. Static and Dynamic Span Analysis

The following static and dynamic span analyses were performed:

- 19018-60-CAL-01004-01-01 Allowable free span (static & dynamic) calculations -26m
- 19018-60-CAL-01004-02-01 Allowable free span (static & dynamic) calculations -8m
- 19018-60-CAL-01004-03-01 Allowable free span (static & dynamic) calculations -17m

(25pages)

Project	**: N05-A Pipeline Design**
Project #	: 19018
Subject	: Static & Dynamic Span Analysis
File #	: 19018-60-CAL-01004-01-01 - Allowable free span (static & dynamic) calculations - 26m.xlsm
Client	: ONE-Dyas
Client File #	: 19018-60-CAL-01004-01-01 - Allowable free span (static & dynamic) calculations - 26m.xlsm

Originator	: EvW	Checked	: PF
Date	: 24/01/2020		
Revision	: 01		

Static & Dynamic Span - 20" x 20.62 mm

Condition Overview

	Pressure (barg)	Temp. (deg. C)	Content (kg/m3)
Installation (P_{in}, T_{in})	2	15	1025
Hydrotest (P_t, T_t)	144	15	1025
Design (P_d, T_d)	111	50	88.7

Pipeline properties

Nominal diameter		OD_{nom} =	20"	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Internal diameter	$ID = OD_{nom} - 2 \cdot d_{nom}$	ID =	466.76	mm
Cross sectional area of steel	$A_s = \frac{\pi}{4} \cdot \{OD_{nom}^2 - ID^2\}$	A_s =	31572	mm^2
Section modulus	$W_s = \frac{\pi}{32} \cdot \frac{\{OD_{nom}^4 - ID^4\}}{OD_{nom}}$	W_s =	3697384	mm^3
Moment of Inertia	$I_s = \frac{\pi}{64} \cdot \{OD_{nom}^4 - ID^4\}$	I_s =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm
Piggyback				
Nominal diameter		$OD_{nom,p}$ =	0	mm
Nominal wall thickness		$d_{nom,p}$ =	0.0	mm

Coating and insulation data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Material

	=	L360NB	
Design temperature	T_d =	50	°C
Yield at ambient/hydrotest temperature	R_e =	360.00	N/mm^2
Yield at design temperature	R_{ed} =	360.00	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	$m/m/^oC$

Weights

		installation (N/m)	hydrotest (N/m)	operation (N/m)
air	line pipe	2431.3	2431.3	2431.3
	content	1720.6	1720.6	148.9
	coating	43.9	43.9	43.9
	piggyback	0.0	0.0	0.0
	coating pb	0.0	0.0	0.0
buoyancy	line pipe	2086.5	2086.5	2086.5
	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:

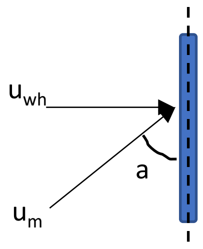
Seawater density		ρ_{sw} =	1025	kg/m³
Maximum water depth		WD_{max} =	29.68	m LAT
Minimum water depth		WD_{min} =	26	m LAT
Other water depth (user input)		WD =	26	m LAT
Storm surge, RP1 yr		ss_{1yr} =	-1.02	m LAT
Storm surge, RP10 yr		ss_{10yr} =	-1.4	m LAT
Storm surge, RP100 yr		ss_{100yr} =	-1.79	m LAT
Storm surge water level, RP1 yr	$SSWL_{1yr} = WD + ss_{1yr}$	$SSWL_{1yr}$ =	24.98	m LAT
Storm surge water level, RP10 yr	$SSWL_{10yr} = WD + ss_{10yr}$	$SSWL_{10yr}$ =	24.6	m LAT
Storm surge water level, RP100 yr	$SSWL_{100yr} = WD + ss_{100yr}$	$SSWL_{100yr}$ =	24.21	m LAT
Highest Astronomical Tide		HAT =	2.72	m

Waves (H_{max} & T_{max}):

Maximum wave height, RP1 yr - installation/hydrotest	$H_{max,1}$ =	11.4	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$ =	10.1	s
Maximum wave height, RP10 yr - operational	$H_{max,10}$ =	14.5	m
Associated maximum wave period, RP10 yr	$T_{ass,10}$ =	10.9	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$ =	16.9	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$ =	11.5	s

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

	1 yr	10 yr	100 yr
$\frac{H}{g \cdot T_{ass}^2}$	0.0114	0.0124	0.0130
$\frac{SWL}{g \cdot T_{ass}^2}$	0.0250	0.0211	0.0187
theory	Stokes	Stokes	Stokes
maximum wave particle velocity (u_{wm})	2.39	3.26	4.00
angle of attack relative to P/L axis (a)	90	90	90
horizontal wave velocity ⊥ to P/L (u_{wh})	2.39	3.26	4.00



Current:

Height above seabed at which velocity is known	z* =	2	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.74	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.84	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	0.96	m/s

Current velocity at reference height: $U_{czr} = u_{st} + u_{ss}$

$U_{czr,1}$ =	0.74	m/s
$U_{czr,10}$ =	0.84	m/s
$U_{czr,100}$ =	0.96	m/s

Angle of attack relative to pipeline axis α_{uc} = 90 deg

Horizontal current velocity ⊥to P/L:

$$u_{cm,perp} = \frac{7}{8} \cdot U_{czr} \cdot \left(\frac{OD_{nom}}{z_r}\right)^{1/7} \cdot \sin(\alpha_{uc})$$

$u_{cm,perp,1}$ =	0.532	m/s
$u_{cm,perp,10}$ =	0.604	m/s
$u_{cm,perp,100}$ =	0.691	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)	1824	N/m
Maximum absolute hydrodynamic force (F_D+F_I), RP100/10 yr (LC 1 operational condition)	4175	N/m
Maximum absolute hydrodynamic force (F_D+F_I), RP10/100 yr (LC 2operational condition)	3124	N/m

Temperatures:

Ambient temperature T_{amb} = 4 deg. C

Project	**: N05-A Pipeline Design**
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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	4619.8	4619.8	2891.0	2891.0	N/m; incl. load factors
Submerged bundle weight, Ws	2324.7	2324.7	595.9	595.9	N/m; incl. load factors
Factored load acting on pipe, q	3071	3193	5045	3796	N/m; $q=\sqrt{\gamma_W{}^2\cdot W_S{}^2+\gamma_H{}^2\cdot(F_D+F_I)^2}$
Pressure	2	144	111	111	barg
DT	11	11	46	46	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	556.4	556.4	N/mm^2

STATIC SPAN LENGTH - INSTALLATION

	Unrestrained pipe tension	Unrestrained pipe compression	Restrained pipe tension	Restrained pipe compression		
Hoop stress	4.4	4.4	4.4	4.4	N/mm^2	$\sigma_H=\frac{(\gamma i\cdot Pi-\gamma e\cdot Pe)\cdot(OD-d_{min})}{2\cdot d_{min}}$
Max. long. Stress	329.4	-325.1	329.4	-325.1	N/mm^2	$\sigma_{max.long.stress}=\frac{\sigma_H\pm\sqrt{-3\cdot\sigma_H^2+4\cdot\sigma_{allow}^2}}{2}$
Long. hoop stress	1.8	1.8	1.3	1.3	N/mm^2	$\sigma_{long.hoop.stress}=\nu\cdot\sigma_H$
Thermal exp. stress	n/a	n/a	-26.8	-26.8	N/mm^2	$\sigma_{thermal}=-\gamma_t\cdot\alpha\cdot E_s\cdot\Delta T$
Max. allow. bending stress	327.3	-326.8	327.3	-299.6	N/mm^2	$\sigma_{b,max}=\sigma_{max.long.stress}-\sigma_{lonh.hoop.stress}-\sigma_{thermal}$
Maximum span	62.8	62.7	62.8	60.1	m	

STATIC SPAN LENGTH - HYDROTEST

	Unrestrained pipe tension	Unrestrained pipe compression	Restrained pipe tension	Restrained pipe compression	
Hoop stress	248.2	248.2	248.2	248.2	N/mm^2
Max. long. Stress	637.3	-389.1	637.3	-389.1	N/mm^2
Long. hoop stress	85.8	85.8	74.5	74.5	N/mm^2
Thermal exp. stress	n/a	n/a	-29.5	-29.5	N/mm^2
Max. allow. bending stress	551.4	-474.9	556.4	-434.0	N/mm^2
Maximum span	79.9	74.2	80.3	70.9	m

STATIC SPAN LENGTH - OPERATION LC1

	Unrestrained pipe tension	Unrestrained pipe compression	Restrained pipe tension	Restrained pipe compression	
Hoop stress	190.3	190.3	190.3	190.3	N/mm^2
Max. long. Stress	626.6	-436.2	626.6	-436.2	N/mm^2
Long. hoop stress	66.2	66.2	57.1	57.1	N/mm^2
Thermal exp. stress	n/a	n/a	-123.3	-123.3	N/mm^2
Max. allow. bending stress	556.4	-502.4	556.4	-370.1	N/mm^2
Maximum span	63.9	60.7	63.9	52.1	m

STATIC SPAN LENGTH - OPERATION LC2

	Unrestrained pipe		Restrained pipe		
	tension	compression	tension	compression	
Hoop stress	190.3	190.3	190.3	190.3	N/mm^2
Max. long. Stress	626.6	-436.2	626.6	-436.2	N/mm^2
Long. hoop stress	66.2	66.2	57.1	57.1	N/mm^2
Thermal exp. stress	n/a	n/a	-123.3	-123.3	N/mm^2
Max. allow. bending stress	556.4	-502.4	556.4	-370.1	N/mm^2
Maximum span	73.6	70.0	73.6	60.0	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)	=	514	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)	=	514	mm

Due to the presense of 2 objects attached to eachother, velocity flow intensification occurs:

$v_{tot} = (v_{wave} + v_{cur}) \times (1 + f_{int})$; $\quad f_{int} = \left\{1 + \left(\frac{D_{ob}^2}{4 \cdot CL^2}\right)\right\}$

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

Vr is set to 1 as conservative value; Vr = 1.0 -

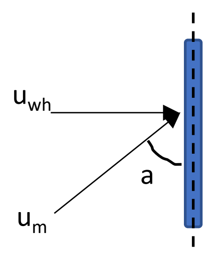
$$f_1 = \frac{a}{2\pi}\sqrt{\frac{E \times I}{m \times L^4}}$$

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	$H_{s,1}$ =	6.5	m
Associated wave period, RP1 yr	$T_{z,1}$ =	9.9	s
Significant wave height, RP10 yr - operational	$H_{s,10}$ =	8.4	m
Associated wave period, RP10 yr	$T_{z,10}$ =	11.3	s
Significant wave height, RP100 yr - operational	$H_{s,100}$ =	9.9	m
Associated wave period, RP100 yr	$T_{z,100}$ =	12.3	s

	1 yr	10 yr	100 yr
$\frac{H}{g \cdot T_{ass}^2}$	0.0068	0.0067	0.0067
$\frac{SWL}{g \cdot T_{ass}^2}$	0.0260	0.0196	0.0163
theory	Stokes	Stokes	Stokes
maximum wave particle velocity (u_{wm})	1.35	2.01	2.56
angle of attack relative to P/L axis (a)	90	90	90
horizontal wave velocity⊥ to P/L (u_{wh})	1.35	2.01	2.56



	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
effective mass	682.9	682.9	522.7	522.7	kg/m
K_s	0.63	0.63	0.49	0.49	-
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}	0.53	0.53	0.60	0.69	m/s, set equal to Ucm, for velocity ratio 0.5
$u_{cm,perp}$	0.53	0.53	0.60	0.69	m/s
D_{ob}	0.0	0.0	0.0	0.0	mm
CL	294.0	294.0	294.0	294.0	mm
f_{int}	0.000	0.000	0.000	0.000	-
$(u_{wh} + u_{cm,perp}) \times (1+0.5 \cdot f_{int}) = v_{tot}$	1.06	1.06	1.21	1.38	m/s
D_o	0.5140	0.5140	0.5140	0.5140	m
f1	2.07	2.07	2.35	2.69	1/s
$L_{span,in}$	25.2	25.2	25.3	23.7	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.

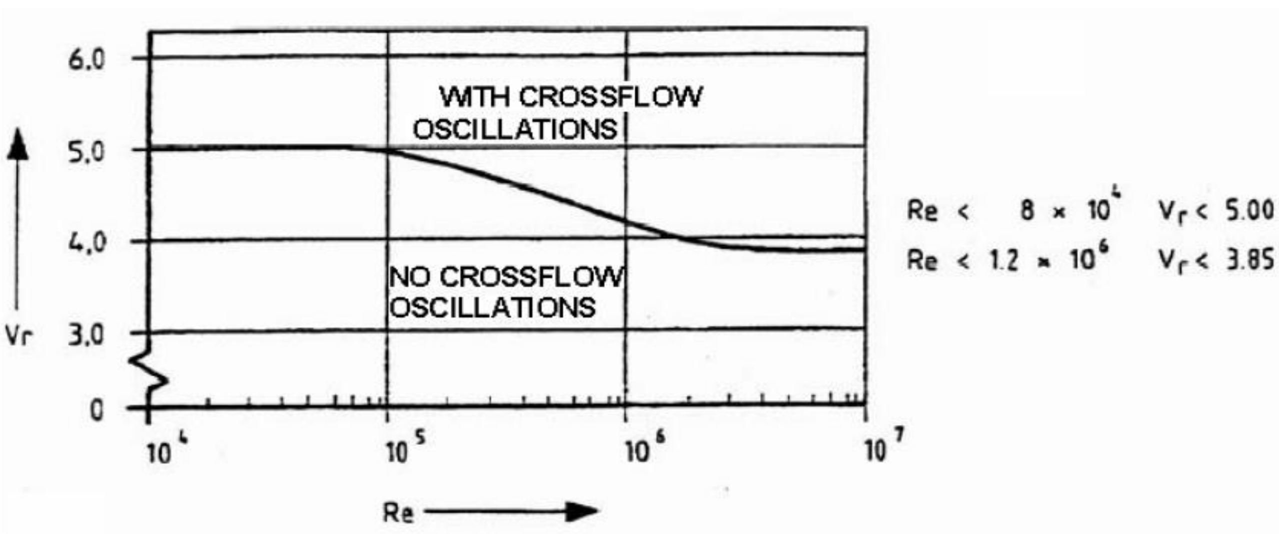
CROSS FLOW VIV:

Oscillation area for cross flow is given by the figure below and depends on the Reynolds number (R_e)

$$R_e = \frac{v \cdot D_o}{v_d}$$

v = horizontal particle velocity (v_{tot})

D_o = outer diameter (incl. coating)	=	514	mm
u_d = dynamic viscosity seawater	u_d =	4.99E-07	m^2/s
Vr is set to 3.85 as conservative value;	Vr =	3.85	-



	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
u_{wh}	1.35	1.35	2.56	2.01	m/s
$u_{cm,perp}$	0.53	0.53	0.60	0.69	m/s
D_{ob}	0.0	0.0	0.0	0.0	mm
CL	294.0	294.0	294.0	294.0	mm
f_{int}	0.000	0.000	0.000	0.000	-
$(u_{wh} + u_{cm,perp}) \times (1+0.5 \cdot f_{int}) = v_{tot}$	1.89	1.89	3.17	2.70	m/s
D_o	0.5140	0.5140	0.5140	0.5140	m
Reynolds nr.	1.94E+06	1.94E+06	3.26E+06	2.78E+06	-
Vr	3.850	3.850	3.850	3.850	-
f1	0.95	0.95	1.60	1.36	1/s
$L_{span,cross}$	37.2	37.2	30.7	33.2	m

SUMMARY - SPAN ANALYSIS

	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
$L_{span,in}$	25.2	25.2	25.3	23.7	m
$L_{span,cross}$	37.2	37.2	30.7	33.2	m

Maximum Span Length = 23.7 m

enersea

Originator	: EvW	Checked	: PF
Date	: 24/01/2020		
Revision	: 01		

Static & Dynamic Span - 10" x 12.7mm

Water depth	WD =	26	m (LAT)
Storm surge	ss =	-1.02	m
Storm surge water level	$SWL = WD + ss$ =	24.98	m
Wave height	H =	11.4	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

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

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

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

Estimate actual wave length, L **143.109** **m**

$$A = SWL / L_O = 0.1568$$

$$B = \frac{SWL}{L} \cdot \tanh\left(\frac{2 \cdot \pi \cdot SWL}{L}\right) = 0.1395$$

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

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

$$D = (C_1 \cdot B)^2 - 4 \cdot (C_2 \cdot B) \cdot (-(A - B)) = 0.1583$$

	-	eq. (I)	eq. (II)
λ1	0.228	-0.0006	0.0000
λ2	Numerator of X < 0		
λ3	-0.228	2.8680	0.0000
λ4	Numerator of X < 0		

Item	Formula	Value	Unit
s	$s = \sinh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.3302	-
c	$c = \cosh\left(\frac{2 \cdot \pi \cdot WL}{L}\right) =$	1.6642	-
A11	$A_{11} = \frac{1}{s} =$	0.7518	-
A13	$A_{13} = \frac{-c^2 \cdot (5 \cdot c^2 + 1)}{8 \cdot s^5} =$	-1.2341	-
	$A_{15} = -\frac{1184 \cdot c^{10} - 1440 \cdot c^8 - 1992 \cdot c^6 + 2641 \cdot c^4 - 249 \cdot c^2 + 18}{1536 \cdot s^{11}} =$	-2.4111	-
A22	$A_{22} = \frac{3}{8 \cdot s^4} =$	0.1198	-
A24	$A_{24} = \frac{192 \cdot c^8 - 424 \cdot c^6 - 312 \cdot c^4 + 480 \cdot c^2 - 17}{768 \cdot s^{10}} =$	0.0907	-
A33	$A_{33} = \frac{13 - 4 \cdot c^2}{64 \cdot s^7} =$	0.0041	-
	$A_{35} = \frac{512 \cdot c^{12} + 4224 \cdot c^{10} - 6800 \cdot c^8 - 12808 \cdot c^6 + 16704 \cdot c^4 - 3154 \cdot c^2 - 107}{4096 \cdot s^{13} \cdot (6 \cdot c^2 - 1)} =$	0.1403	-
A44	$A_{44} = \frac{80 \cdot c^6 - 816 \cdot c^4 + 1338 \cdot c^2 - 197}{1536 \cdot s^{10} \cdot (6 \cdot c^2 - 1)} =$	-0.0025	-

$$A_{55} = -\frac{2880 \cdot c^{10} - 72480 \cdot c^{8} + 324000 \cdot c^{6} - 432000 \cdot c^{4} + 163470 \cdot c^{2} - 16245}{61440 \cdot s^{11} \cdot (6 \cdot c^{2} - 1) \cdot (8 \cdot c^{4} - 11 \cdot c^{2} + 3)} =$$ -0.0003 -

B22 $$B_{22} = \frac{(2 \cdot c^{2} + 1) \cdot c}{4 \cdot s^{3}} =$$ 1.1558 -

B24 $$B_{24} = \frac{c \cdot (272 \cdot c^{8} - 504 \cdot c^{6} - 192 \cdot c^{4} + 322 \cdot c^{2} + 21)}{384 \cdot s^{9}} =$$ 1.5738 -

B33 $$B_{33} = \frac{3 \cdot (8 \cdot c^{6} + 1)}{64 \cdot s^{6}} =$$ 1.4462 -

$$B_{35} = \frac{88128 \cdot c^{14} - 208224 \cdot c^{12} + 70848 \cdot c^{10} + 54000 \cdot c^{8} - 21816 \cdot c^{6} + 6264 \cdot c^{4} - 54 \cdot c^{2} - 81}{12288 \cdot s^{12} \cdot (6 \cdot c^{2} - 1)} =$$
= 5.1741 -

B44 $$B_{44} = c \cdot \frac{768 \cdot c^{10} - 488 \cdot c^{8} - 48 \cdot c^{6} + 48 \cdot c^{4} + 106 \cdot c^{2} - 21}{384 \cdot s^{9} \cdot (6 \cdot c^{2} - 1)} =$$ 2.0437 -

$$B_{55} = \frac{192000 \cdot c^{16} - 26720 \cdot c^{14} + 83680 \cdot c^{12} + 20160 \cdot c^{10} - 7280 \cdot c^{8} + 7160 \cdot c^{6} - 1800 \cdot c^{4} - 1050 \cdot c^{2} + 225}{12288 \cdot s^{10} \cdot (8 \cdot c^{4} - 11 \cdot c^{2} + 3) \cdot (6 \cdot c^{2} - 1)} =$$
= 3.3404 -

C1 $$C_{1} = \frac{8 \cdot c^{4} - 8 \cdot c^{2} + 9}{8 \cdot s^{4}} =$$ 1.9244 -

$$C_{2} = \frac{3840 \cdot c^{12} - 4096 \cdot c^{10} + 2592 \cdot c^{8} - 1008 \cdot c^{6} + 5944 \cdot c^{4} - 1830 \cdot c^{2} + 147}{512 \cdot s^{10} \cdot (6 \cdot c^{2} - 1)} =$$ 8.9186 -

C3 $$C_{3} = -\frac{1}{4 \cdot c \cdot s} =$$ -0.1129 -

C4 $$C_{4} = \frac{12 \cdot c^{8} + 36 \cdot c^{6} - 162 \cdot c^{4} + 141 \cdot c^{2} - 27}{192 \cdot c \cdot s^{9}} =$$ 0.1420 -

K1 $$K_{1} = \lambda \cdot A_{11} + \lambda^{3} \cdot A_{13} + \lambda^{5} \cdot A_{15} =$$ 0.1553 -

K2	$K_2 = \lambda^2 \cdot A_{22} + \lambda^4 \cdot A_{24} =$	0.0065	-
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	-

Project	**: N05-A Pipeline Design**
Project #	: 19018
Subject	: Static & Dynamic Span Analysis
File #	: 19018-60-CAL-01004-01-01 - Allowable free span (static & dynamic) calculations - 26m.xlsm
Client	: ONE-Dyas
Client File #	:

Originator	: EvW	Checked	: PF
Date	: 24/01/2020		
Revision	: 01		

Horizontal wave particle velocities

Water depth at which data required, z (w.r.t. seabed) 0.5080 m

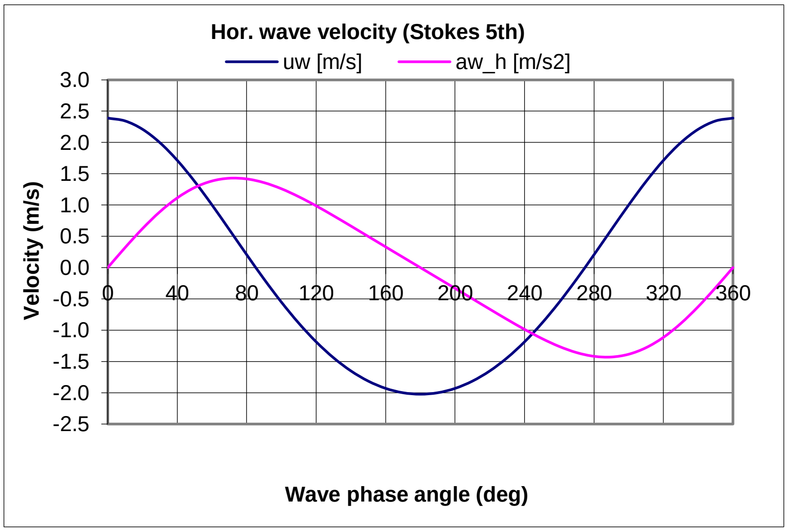
Horizontal velocity, u_w

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

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	2.3895	0.0000
10.00	2.3444	0.3205
20.00	2.2113	0.6233
30.00	1.9978	0.8921
40.00	1.7152	1.1138
50.00	1.3781	1.2793
60.00	1.0030	1.3842
70.00	0.6070	1.4288
80.00	0.2065	1.4177
90.00	-0.1839	1.3583
100.00	-0.5520	1.2602
110.00	-0.8883	1.1334
120.00	-1.1862	0.9871
130.00	-1.4411	0.8289
140.00	-1.6507	0.6647
150.00	-1.8139	0.4983
160.00	-1.9303	0.3317
170.00	-2.0000	0.1656
180.00	-2.0233	0.0000
190.00	-2.0000	-0.1656
200.00	-1.9303	-0.3317



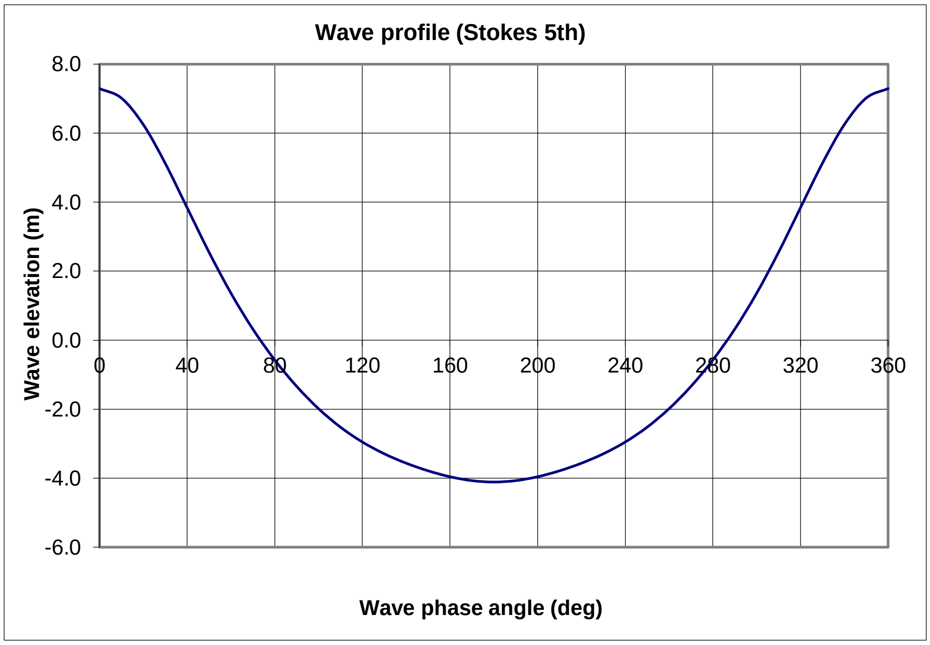
210.00	-1.8139	-0.4983
220.00	-1.6507	-0.6647
230.00	-1.4411	-0.8289
240.00	-1.1862	-0.9871
250.00	-0.8883	-1.1334
260.00	-0.5520	-1.2602
270.00	-0.1839	-1.3583
280.00	0.2065	-1.4177
290.00	0.6070	-1.4288
300.00	1.0030	-1.3842
310.00	1.3781	-1.2793
320.00	1.7152	-1.1138
330.00	1.9978	-0.8921
340.00	2.2113	-0.6233
350.00	2.3444	-0.3205
360.00	2.3895	0.0000

U_{wm} = max. wave particle velocity = 2.39 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	7.2930
10.00	7.0176
20.00	6.2468
30.00	5.1259
40.00	3.8385
50.00	2.5483
60.00	1.3614
70.00	0.3208
80.00	-0.5742
90.00	-1.3393
100.00	-1.9865
110.00	-2.5217
120.00	-2.9522
130.00	-3.2934
140.00	-3.5660
150.00	-3.7866
160.00	-3.9586
170.00	-4.0716
180.00	-4.1115
190.00	-4.0716
200.00	-3.9586
210.00	-3.7866
220.00	-3.5660
230.00	-3.2934
240.00	-2.9522
250.00	-2.5217
260.00	-1.9865
270.00	-1.3393
280.00	-0.5742
290.00	0.3208
300.00	1.3614
310.00	2.5483
320.00	3.8385
330.00	5.1259
340.00	6.2468
350.00	7.0176
360.00	7.2930



Static & Dynamic Span - 20" x 20.62 mm

Condition Overview

	Pressure (barg)	Temp. (deg. C)	Content (kg/m3)
Installation (P_{in}, T_{in})	2	15	1025
Hydrotest (P_t, T_t)	144	15	1025
Design (P_d, T_d)	111	50	88.7

Pipeline properties				
Nominal diameter		OD_{nom} =	20"	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Internal diameter	$ID = OD_{nom} - 2\cdot d_{nom}$	ID =	466.76	mm
Cross sectional area of steel	$A_s = \frac{\pi}{4}\cdot\{OD_{nom}^2 - ID^2\}$	A_s =	31572	mm^2
Section modulus	$W_s = \frac{\pi}{32}\cdot\frac{\{OD_{nom}^4 - ID^4\}}{OD_{nom}}$	W_s =	3697384	mm^3
Moment of Inertia	$I_s = \frac{\pi}{64}\cdot\{OD_{nom}^4 - ID^4\}$	I_s =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom}\cdot\{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2\cdot\{OD_{nom} + (OD_{nom} - 2\cdot t_{min})\}$	OD_g =	491.9	mm
Piggyback				
Nominal diameter		$OD_{nom,p}$ =	0	mm
Nominal wall thickness		$d_{nom,p}$ =	0.0	mm
Coating and insulation data				
Thickness line pipe		=	3	mm
Thickness piggyback		=	0	mm
Density		=	930	kg/m^3
Constants				
gravitational acceleration		g =	9.81	m/s^2
Material		=	L360NB	
Design temperature		T_d =	50	°C
Yield at ambient/hydrotest temperature		R_e =	360.00	N/mm^2
Yield at design temperature		R_{ed} =	360.00	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	2431.3	2431.3	2431.3
	content	1720.6	1720.6	148.9
	coating	43.9	43.9	43.9
	piggyback	0.0	0.0	0.0
	coating pb	0.0	0.0	0.0
buoyancy	line pipe	2086.5	2086.5	2086.5
	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

Project	**: N05-A Pipeline Design**
Project #	: 19018
Subject	: Static & Dynamic Span Analysis
File #	: 19018-60-CAL-01004-02-01 - Allowable free span (static & dynamic) calculations - 8m.xlsm
Client	: ONE-Dyas
Client File #	: 19018-60-CAL-01004-02-01 - Allowable free span (static & dynamic) calculations - 8m.xlsm

Originator	: EvW	Checked	: PF
Date	: 27/01/2020		
Revision	: 01		

Environmental conditions

Water depths:

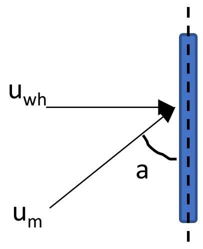
Seawater density		ρ_{sw} =	1025	kg/m³
Maximum water depth		WD_{max} =	11.5	m LAT
Minimum water depth		WD_{min} =	8	m LAT
Other water depth (user input)		WD =	8	m LAT
Storm surge, RP1 yr		ss_{1yr} =	-0.14	m LAT
Storm surge, RP10 yr		ss_{10yr} =	-0.46	m LAT
Storm surge, RP100 yr		ss_{100yr} =	-0.78	m LAT
Storm surge water level, RP1 yr	$SSWL_{1yr} = WD + ss_{1yr}$	$SSWL_{1yr}$ =	7.86	m LAT
Storm surge water level, RP10 yr	$SSWL_{10yr} = WD + ss_{10yr}$	$SSWL_{10yr}$ =	7.54	m LAT
Storm surge water level, RP100 yr	$SSWL_{100yr} = WD + ss_{100yr}$	$SSWL_{100yr}$ =	7.22	m LAT
Highest Astronomical Tide		HAT =	3.5	m

Waves (H_{max} & T_{max}):

Maximum wave height, RP1 yr - installation/hydrotest	$H_{max,1}$ =	5.2	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$ =	7.7	s
Maximum wave height, RP10 yr - operational	$H_{max,10}$ =	5.7	m
Associated maximum wave period, RP10 yr	$T_{ass,10}$ =	7.9	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$ =	6.2	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$ =	8.1	s

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

	1 yr	10 yr	100 yr
$\frac{H}{g \cdot T_{ass}^2}$	0.0089	0.0093	0.0096
$\frac{SWL}{g \cdot T_{ass}^2}$	0.0135	0.0123	0.0112
theory	Wave particle velocity directly from metocean data		
maximum wave particle velocity (u_{wm})	1.30	1.50	1.60
angle of attack relative to P/L axis (a)	90	90	90
horizontal wave velocity ⊥ to P/L (u_{wh})	1.30	1.50	1.60



Current:

Height above seabed at which velocity is known	z* =	1	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.89	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	1	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	1.12	m/s

Current velocity at reference height: $U_{czr} = u_{st} + u_{ss}$

$U_{czr,1}$ =	0.89	m/s
$U_{czr,10}$ =	1	m/s
$U_{czr,100}$ =	1.12	m/s

Angle of attack relative to pipeline axis α_{uc} = 90 deg

Horizontal current velocity ⊥ to P/L:

$$u_{cm,perp} = \frac{7}{8} \cdot U_{czr} \cdot \left(\frac{OD_{nom}}{z_r}\right)^{1/7} \cdot \sin(\alpha_{uc})$$

$u_{cm,perp,1}$ =	0.707	m/s
$u_{cm,perp,10}$ =	0.794	m/s
$u_{cm,perp,100}$ =	0.890	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)	891	N/m
Maximum absolute hydrodynamic force (F_D+F_I), RP100/10 yr (LC 1 operational condition)	1269	N/m
Maximum absolute hydrodynamic force (F_D+F_I), RP10/100 yr (LC 2operational condition)	1264	N/m

Temperatures:

Ambient temperature T_{amb} = 4 deg. C

Project	**: N05-A Pipeline Design**		
Project #	: 19018		
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File #	: 19018-60-CAL-01004-02-01 - Allowable free span (static & dynamic) calculations - 8m.xlsm		
Client	: ONE-Dyas		
Client File #	: 19018-60-CAL-01004-02-01 - Allowable free span (static & dynamic) calculations - 8m.xlsm		
Originator	: EvW	Checked	: PF
Date	: 27/01/2020		
Revision	: 01		

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	4619.8	4619.8	2891.0	2891.0	N/m; incl. load factors
Submerged bundle weight, Ws	2324.7	2324.7	595.9	595.9	N/m; incl. load factors
Factored load acting on pipe, q	2523	2559	1635	1629	N/m; $q = \sqrt{\gamma_W{}^2 \cdot W_S{}^2 + \gamma_H{}^2 \cdot (F_D + F_I)^2}$
Pressure	2	144	111	111	barg
DT	11	11	46	46	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	556.4	556.4	N/mm^2

STATIC SPAN LENGTH - INSTALLATION

	Unrestrained pipe		Restrained pipe			
	tension	compression	tension	compression		
Hoop stress	1.3	1.3	1.3	1.3	N/mm^2	$\sigma_H = \frac{(\gamma i \cdot Pi - \gamma e \cdot Pe) \cdot (OD - d_{min})}{2 \cdot d_{min}}$
Max. long. Stress	327.9	-326.6	327.9	-326.6	N/mm^2	$\sigma_{max.long.stress} = \frac{\sigma_H \pm \sqrt{-3 \cdot \sigma_H^2 + 4 \cdot \sigma_{allow}^2}}{2}$
Long. hoop stress	0.7	0.7	0.4	0.4	N/mm^2	$\sigma_{long.hoop.stress} = v \cdot \sigma_H$
Thermal exp. stress	n/a	n/a	-26.8	-26.8	N/mm^2	$\sigma_{thermal} = -\gamma_t \cdot \alpha \cdot E_s \cdot \Delta T$
Max. allow. bending stress	327.3	327.3	327.3	-300.2	N/mm^2	$\sigma_{b,max} = \sigma_{max.long.stress} - \sigma_{lonh.hoop.stress} - \sigma_{thermal}$
Maximum span	69.3	69.3	69.3	66.3	m	

STATIC SPAN LENGTH - HYDROTEST

	Unrestrained pipe		Restrained pipe		
	tension	compression	tension	compression	
Hoop stress	251.2	251.2	251.2	251.2	N/mm^2
Max. long. Stress	637.7	-386.4	637.7	-386.4	N/mm^2
Long. hoop stress	85.8	85.8	75.4	75.4	N/mm^2
Thermal exp. stress	n/a	n/a	-29.5	-29.5	N/mm^2
Max. allow. bending stress	551.8	-472.3	556.4	-432.3	N/mm^2
Maximum span	89.3	82.6	89.7	79.0	m

STATIC SPAN LENGTH - OPERATION LC1

	Unrestrained pipe		Restrained pipe		
	tension	compression	tension	compression	
Hoop stress	193.3	193.3	193.3	193.3	N/mm^2
Max. long. Stress	627.2	-433.9	627.2	-433.9	N/mm^2
Long. hoop stress	66.2	66.2	58.0	58.0	N/mm^2
Thermal exp. stress	n/a	n/a	-123.3	-123.3	N/mm^2
Max. allow. bending stress	556.4	-500.1	556.4	-368.6	N/mm^2
Maximum span	112.2	106.4	112.2	91.3	m

STATIC SPAN LENGTH - OPERATION LC2

	Unrestrained pipe		Restrained pipe		
	tension	compression	tension	compression	
Hoop stress	193.3	193.3	193.3	193.3	N/mm^2
Max. long. Stress	627.2	-433.9	627.2	-433.9	N/mm^2
Long. hoop stress	66.2	66.2	58.0	58.0	N/mm^2
Thermal exp. stress	n/a	n/a	-123.3	-123.3	N/mm^2
Max. allow. bending stress	556.4	-500.1	556.4	-368.6	N/mm^2
Maximum span	112.4	106.5	112.4	91.5	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

$$K_s = \frac{2m \text{ x } \delta}{\rho_w \text{ x } D_o^2}$$

Where,

d = damping factor water: 0.02 x 2 x π	=	0.126	-
r_w = seawater density	=	1025	kg/m[3]
D_o = outer diameter (incl. coating)	=	514	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)	=	514	mm

Due to the presense of 2 objects attached to eachother, velocity flow intensification occurs:

$v_{tot} = (v_{wave} + v_{cur}) \text{ x } (1 + f_{int})$; $f_{int} = \left\{1 + \left(\frac{D_{ob}^2}{4 \cdot CL^2}\right)\right\}$

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 $1{,}0 \leq V_r \leq 3{,}5$ then oscillation occurs => Vr<1,0 design criterium

Vr is set to 1 as conservative value; Vr = 1.0 -

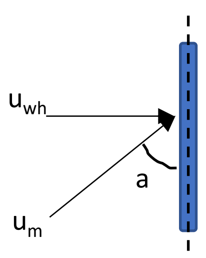
$$f_1 = \frac{a}{2\pi}\sqrt{\frac{E \times I}{m \times L^4}}$$

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	$H_{s,1}$ =	3.9	m
Associated wave period, RP1 yr	$T_{z,1}$ =	6.4	s
Significant wave height, RP10 yr - operational	$H_{s,10}$ =	4.1	m
Associated wave period, RP10 yr	$T_{z,10}$ =	6.5	s
Significant wave height, RP100 yr - operational	$H_{s,100}$ =	4.2	m
Associated wave period, RP100 yr	$T_{z,100}$ =	6.6	s

	1 yr	10 yr	100 yr
$\frac{H}{g \cdot T_{ass}^2}$	0.0097	0.0099	0.0098
$\frac{SWL}{g \cdot T_{ass}^2}$	0.0196	0.0182	0.0169
theory	Wave particle velocity directly from metocean data		
maximum wave particle velocity (u_{wm})	1.30	1.50	1.60
angle of attack relative to P/L axis (a)	90	90	90
horizontal wave velocity⊥ to P/L (u_{wh})	1.30	1.50	1.60



	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
effective mass	682.9	682.9	522.7	522.7	kg/m
K_s	0.63	0.63	0.49	0.49	-
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}	0.71	0.71	0.79	0.89	m/s, set equal to Ucm, for velocity ratio 0.5
$u_{cm,perp}$	0.71	0.71	0.79	0.89	m/s
D_{ob}	0.0	0.0	0.0	0.0	mm
CL	294.0	294.0	294.0	294.0	mm
f_{int}	0.000	0.000	0.000	0.000	-
$(u_{wh} + u_{cm,perp}) \times (1+0.5 \cdot f_{int}) = v_{tot}$	1.41	1.41	1.59	1.78	m/s
D_o	0.5140	0.5140	0.5140	0.5140	m
f1	2.75	2.75	3.09	3.46	1/s
$L_{span,in}$	21.9	21.9	22.1	20.9	m

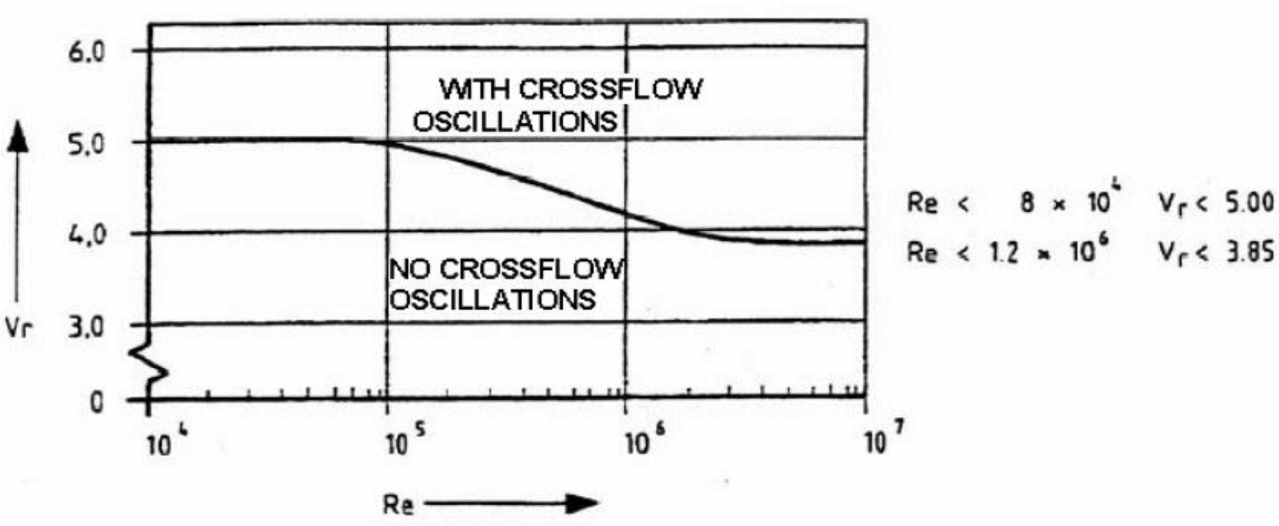
note: f_{int} is taken into account for 50% as system doesn't instantaneously respond and vortices occur in a relatively steady state environment, which this isn't.

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)	=	514	mm
u_d = dynamic viscosity seawater	u_d =	4.99E-07	m^2/s
Vr is set to 3.85 as conservative value;	Vr =	3.85	-



	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
u_{wh}	1.30	1.30	1.60	1.50	m/s
$u_{cm,perp}$	0.71	0.71	0.79	0.89	m/s
D_{ob}	0.0	0.0	0.0	0.0	mm
CL	294.0	294.0	294.0	294.0	mm
f_{int}	0.000	0.000	0.000	0.000	-
$(u_{wh} + u_{cm,perp}) \times (1+0.5 \cdot f_{int}) = v_{tot}$	2.01	2.01	2.39	2.39	m/s
D_o	0.5140	0.5140	0.5140	0.5140	m
Reynolds nr.	2.07E+06	2.07E+06	2.47E+06	2.46E+06	-
Vr	3.850	3.850	3.850	3.850	-
f1	1.01	1.01	1.21	1.21	1/s
$L_{span,cross}$	36.0	36.0	35.3	35.3	m

SUMMARY - SPAN ANALYSIS

	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
$L_{span,in}$	21.9	21.9	22.1	20.9	m
$L_{span,cross}$	36.0	36.0	35.3	35.3	m

Maximum Span Length = 20.9 m

Project	**: N05-A Pipeline Design**
Project #	: 19018
Subject	: Static & Dynamic Span Analysis
File #	: 19018-60-CAL-01004-03-02 - Allowable free span (static & dynamic) calculations - 17m.xlsm
Client	: ONE-Dyas
Client File #	: 19018-60-CAL-01004-03-02 - Allowable free span (static & dynamic) calculations - 17m.xlsm

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Originator	: EvW	Checked	: PF
Date	: 12-3-2020		
Revision	: 02		

Static & Dynamic Span - 20" x 20.62 mm

Condition Overview

	Pressure (barg)	Temp. (deg. C)	Content (kg/m3)
Installation (P_{in}, T_{in})	2	15	1025
Hydrotest (P_t, T_t)	144	15	1025
Design (P_d, T_d)	111	50	88.7

Pipeline properties

Nominal diameter		OD_{nom} =	20"	
Nominal diameter		OD_{nom} =	508	mm
Nominal wall thickness		d_{nom} =	20.62	mm
Internal diameter	$ID = OD_{nom} - 2 \cdot d_{nom}$	ID =	466.76	mm
Cross sectional area of steel	$A_s = \frac{\pi}{4} \cdot \{OD_{nom}^2 - ID^2\}$	A_s =	31572	mm^2
Section modulus	$W_s = \frac{\pi}{32} \cdot \frac{\{OD_{nom}^4 - ID^4\}}{OD_{nom}}$	W_s =	3697384	mm^3
Moment of Inertia	$I_s = \frac{\pi}{64} \cdot \{OD_{nom}^4 - ID^4\}$	I_s =	939135656	mm^4
Corrosion allowance		CA =	3	mm
Fabrication Tolerance		f_{tol} =	7.25	%
Minimum wall thickness	$d_{min} = d_{nom} \cdot \{1 - f_{tol}\} - CA$	d_{min} =	16.1	mm
Average pipe diameter	$OD_g = 1/2 \cdot \{OD_{nom} + (OD_{nom} - 2 \cdot t_{min})\}$	OD_g =	491.9	mm
Piggyback				
Nominal diameter		$OD_{nom,p}$ =	0	mm
Nominal wall thickness		$d_{nom,p}$ =	0.0	mm

Coating and insulation data

Thickness line pipe	=	3	mm
Thickness piggyback	=	0	mm
Density	=	930	kg/m^3

Constants

gravitational acceleration	g =	9.81	m/s^2

Material

	=	L360NB	
Design temperature	T_d =	50	°C
Yield at ambient/hydrotest temperature	R_e =	360.00	N/mm^2
Yield at design temperature	R_{ed} =	360.00	N/mm^2
Density	ρ_{st} =	7850	kg/m3
Youngs modulus	E_s =	210000	N/mm^2
Poisson's ratio	υ =	0.3	-
Linear thermal expansion coefficient	α =	1.16E-05	m/m/°C

Weights

		installation (N/m)	hydrotest (N/m)	operation (N/m)
air	line pipe	2431.3	2431.3	2431.3
	content	1720.6	1720.6	148.9
	coating	43.9	43.9	43.9
	piggyback	0.0	0.0	0.0
	coating pb	0.0	0.0	0.0
buoyancy	line pipe	2086.5	2086.5	2086.5
	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

Project	**: N05-A Pipeline Design**
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Environmental conditions

Water depths:

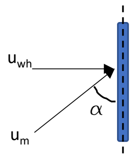
Seawater density		ρ_{sw} =	1025	kg/m³
Maximum water depth		WD_{max} =	20.59	m LAT
Minimum water depth		WD_{min} =	17	m LAT
Other water depth (user input)		WD =	17	m LAT
Storm surge, RP1 yr		ss_{1yr} =	-0.58	m LAT
Storm surge, RP10 yr		ss_{10yr} =	-0.93	m LAT
Storm surge, RP100 yr		ss_{100yr} =	-1.285	m LAT
Storm surge water level, RP1 yr	$SSWL_{1yr} = WD + ss_{1yr}$	$SSWL_{1yr}$ =	16.42	m LAT
Storm surge water level, RP10 yr	$SSWL_{10yr} = WD + ss_{10yr}$	$SSWL_{10yr}$ =	16.07	m LAT
Storm surge water level, RP100 yr	$SSWL_{100yr} = WD + ss_{100yr}$	$SSWL_{100yr}$ =	15.715	m LAT
Highest Astronomical Tide		HAT =	3.11	m

Waves (H_{max} & T_{max}):

Maximum wave height, RP1 yr - installation/hydrotest	$H_{max,1}$ =	8.3	m
Associated maximum wave period, RP1 yr	$T_{ass,1}$ =	8.9	s
Maximum wave height, RP10 yr - operational	$H_{max,10}$ =	10.1	m
Associated maximum wave period, RP10 yr	$T_{ass,10}$ =	9.4	s
Maximum wave height, RP100 yr - operational	$H_{max,100}$ =	11.55	m
Associated maximum wave period, RP100 yr	$T_{ass,100}$ =	9.8	s

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

	1 yr	10 yr	100 yr
$\frac{H}{g \cdot T_{ass}^2}$	0.0107	0.0117	0.0123
$\frac{SWL}{g \cdot T_{ass}^2}$	0.0211	0.0185	0.0167
theory	interpolation between data of 8 and 26m water depth		
maximum wave particle velocity (u_{wm})	1.85	2.38	2.80
angle of attack relative to P/L axis (α)	90	90	90
horizontal wave velocity ⊥ to P/L (u_{wh})	1.85	2.38	2.80



Current:

Height above seabed at which velocity is known	z* =	1	m
Spring tide	u_{st} =	0	m/s
Storm surge, RP1 yr	$u_{ss,1}$ =	0.82	m/s
Storm surge, RP10 yr	$u_{ss,10}$ =	0.92	m/s
Storm surge, RP100 yr	$u_{ss,100}$ =	1.04	m/s

Current velocity at reference height: $U_{czr} = u_{st} + u_{ss}$

$U_{czr,1}$ =	0.82	m/s
$U_{czr,10}$ =	0.92	m/s
$U_{czr,100}$ =	1.04	m/s

Angle of attack relative to pipeline axis α_{uc} = 90 deg

Horizontal current velocity ⊥ to P/L:

$$u_{cm,perp} = \frac{7}{8} \cdot U_{czr} \cdot \left(\frac{OD_{nom}}{z_r}\right)^{1/7} \cdot \sin(\alpha_{uc})$$

$u_{cm,perp,1}$ =	0.647	m/s
$u_{cm,perp,10}$ =	0.731	m/s
$u_{cm,perp,100}$ =	0.826	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)	1392	N/m
Maximum absolute hydrodynamic force (F_D+F_I), RP100/10 yr (LC 1 operational condition)	2976	N/m
Maximum absolute hydrodynamic force (F_D+F_I), RP10/100 yr (LC 2operational condition)	2360	N/m

Temperatures:

Ambient temperature T_{amb} = 4 deg. C

Project : **N05-A Pipeline Design**
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Originator : EvW
Date : 12-3-2020
Revision : 02
Checked : PF

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	4619.8	4619.8	2891.0	2891.0	N/m; incl. load factors
Submerged bundle weight, Ws	2324.7	2324.7	595.9	595.9	N/m; incl. load factors
Factored load acting on pipe, q	2784	2863	3621	2894	N/m; $q = \sqrt{\gamma_W{}^2 \cdot W_S{}^2 + \gamma_H{}^2 \cdot (F_D + F_I)^2}$
Pressure	2	144	111	111	barg
ΔT	11	11	46	46	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	556.4	556.4	N/mm²

STATIC SPAN LENGTH - INSTALLATION

	Unrestrained pipe		Restrained pipe			
	tension	compression	tension	compression		
Hoop stress	2.9	2.9	2.9	2.9	N/mm²	$\sigma_H = \frac{(\gamma i \cdot Pi - \gamma e \cdot Pe) \cdot (OD - d_{min})}{2 \cdot d_{min}}$
Max. long. Stress	328.7	-325.8	328.7	-325.8	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	1.2	1.2	0.9	0.9	N/mm²	$\sigma_{long.hoop.stress} = \nu \cdot \sigma_H$
Thermal exp. stress	n/a	n/a	-26.8	-26.8	N/mm²	$\sigma_{thermal} = -\gamma_t \cdot \alpha \cdot E_s \cdot \Delta T$
Max. allow. bending stress	327.3	-327.1	327.3	-299.9	N/mm²	$\sigma_{b,max} = \sigma_{max.long.stress} - \sigma_{lonh.hoop.stress} - \sigma_{thermal}$
Maximum span	65.9	65.9	65.9	63.1	m	

STATIC SPAN LENGTH - HYDROTEST

	Unrestrained pipe		Restrained pipe		
	tension	compression	tension	compression	
Hoop stress	249.7	249.7	249.7	249.7	N/mm²
Max. long. Stress	637.5	-387.8	637.5	-387.8	N/mm²
Long. hoop stress	85.8	85.8	74.9	74.9	N/mm²
Thermal exp. stress	n/a	n/a	-29.5	-29.5	N/mm²
Max. allow. bending stress	551.6	-473.6	556.4	-433.2	N/mm²
Maximum span	84.4	78.2	84.8	74.8	m

STATIC SPAN LENGTH - OPERATION LC1

	Unrestrained pipe		Restrained pipe		
	tension	compression	tension	compression	
Hoop stress	191.8	191.8	191.8	191.8	N/mm²
Max. long. Stress	626.9	-435.1	626.9	-435.1	N/mm²
Long. hoop stress	66.2	66.2	57.6	57.6	N/mm²
Thermal exp. stress	n/a	n/a	-123.3	-123.3	N/mm²
Max. allow. bending stress	556.4	-501.2	556.4	-369.4	N/mm²
Maximum span	75.4	71.5	75.4	61.4	m

STATIC SPAN LENGTH - OPERATION LC2

	Unrestrained pipe		Restrained pipe		
	tension	compression	tension	compression	
Hoop stress	191.8	191.8	191.8	191.8	N/mm^2
Max. long. Stress	626.9	-435.1	626.9	-435.1	N/mm^2
Long. hoop stress	66.2	66.2	57.6	57.6	N/mm^2
Thermal exp. stress	n/a	n/a	-123.3	-123.3	N/mm^2
Max. allow. bending stress	556.4	-501.2	556.4	-369.4	N/mm^2
Maximum span	84.3	80.0	84.3	68.7	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

$$K_s = \frac{2m \text{ x } \delta}{\rho_w \text{ x } D_o^2}$$

Where,

δ = damping factor water: 0.02 x 2 x π	=	0.126	-
ρ_w = seawater density	=	1025	kg/m^3
D_o = outer diameter (incl. coating)	=	514	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)	=	514	mm

Due to the presense of 2 objects attached to eachother, velocity flow intensification occurs:

$v_{tot} = (v_{wave} + v_{cur}) \times (1 + f_{int})$; $f_{int} = \left\{1 + \left(\frac{D_{ob}^2}{4 \cdot CL^2}\right)\right\}$

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

Vr is set to 1 as conservative value; Vr = 1.0 -

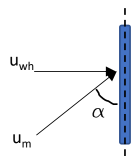
$$f_1 = \frac{a}{2\pi}\sqrt{\frac{E \times I}{m \times L^4}}$$

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	$H_{s,1}$ =	5.2	m
Associated wave period, RP1 yr	$T_{z,1}$ =	8.2	s
Significant wave height, RP10 yr - operational	$H_{s,10}$ =	6.25	m
Associated wave period, RP10 yr	$T_{z,10}$ =	8.9	s
Significant wave height, RP100 yr - operational	$H_{s,100}$ =	7.05	m
Associated wave period, RP100 yr	$T_{z,100}$ =	9.45	s

	1 yr	10 yr	100 yr
$\frac{H}{g \cdot T_{ass}^2}$	0.0080	0.0080	0.0080
$\frac{SWL}{g \cdot T_{ass}^2}$	0.0252	0.0207	0.0179
theory	interpolation between data of 8 and 26m water depth		
maximum wave particle velocity (u_{wm})	1.33	1.76	2.08
angle of attack relative to P/L axis (α)	90	90	90
horizontal wave velocity⊥ to P/L (u_{wh})	1.33	1.76	2.08



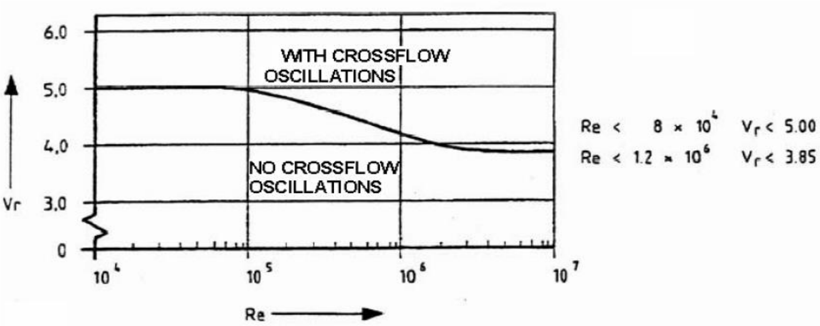
	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
effective mass	682.9	682.9	522.7	522.7	kg/m
K_s	0.63	0.63	0.49	0.49	-
In-line VIV	yes	yes	yes	yes	-
cross flow VIV	yes	yes	yes	yes	-
Vr	1.00	1.00	1.00	1.00	-
u_{wh}	0.65	0.65	0.73	0.83	m/s, set equal to Ucm, for velocity ratio 0.5
$u_{cm,perp}$	0.65	0.65	0.73	0.83	m/s
D_{ob}	0.0	0.0	0.0	0.0	mm
CL	294.0	294.0	294.0	294.0	mm
f_{int}	0.000	0.000	0.000	0.000	-
$(u_{wh} + u_{cm,perp}) \times (1+0.5 \cdot f_{int}) = v_{tot}$	1.29	1.29	1.46	1.65	m/s
D_o	0.5140	0.5140	0.5140	0.5140	m
f1	2.52	2.52	2.84	3.21	1/s
$L_{span,in}$	22.9	22.9	23.0	21.6	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)

$$R_e = \frac{v \cdot D_o}{\upsilon_d}$$

v = horizontal particle velocity (v_{tot})
D_o = outer diameter (incl. coating) = 514 mm
υ_d = dynamic viscosity seawater υ_d = 4.99E-07 m^2/s
Vr is set to 3.85 as conservative value; Vr = 3.85 -



	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
u_{wh}	1.33	1.33	2.08	1.76	m/s
$u_{cm,perp}$	0.65	0.65	0.73	0.83	m/s
D_{ob}	0.0	0.0	0.0	0.0	mm
CL	294.0	294.0	294.0	294.0	mm
f_{int}	0.000	0.000	0.000	0.000	-
$(u_{wh} + u_{cm,perp}) \times (1+0.5 \cdot f_{int}) = v_{tot}$	1.97	1.97	2.81	2.58	m/s
D_o	0.5140	0.5140	0.5140	0.5140	m
Reynolds nr.	2.03E+06	2.03E+06	2.90E+06	2.66E+06	-
Vr	3.850	3.850	3.850	3.850	-
f1	1.00	1.00	1.42	1.30	1/s
$L_{span,cross}$	36.4	36.4	32.6	34.0	m

SUMMARY - SPAN ANALYSIS

	Installation	Hydrotest	LC 1 Operation	LC 2 Operation	
$L_{span,in}$	22.9	22.9	23.0	21.6	m
$L_{span,cross}$	36.4	36.4	32.6	34.0	m

Maximum Span Length = 21.6 m

D. Analytical Upheaval Buckling Analysis

The following documents are included:

- 19018-60-CAL-01005-01-01 Upheaval Buckling Analysis – 43 deg

(4 pages)

Client	**:** ONE-Dyas
Project	**:** N05A Flowline
Project No.	**:** 19018
Subject	**:** Pipeline Upheaval Buckling - analytical
Doc. No.	**:** 19018-60-CAL-01005-01
Client Doc. No.	**:** -

Calc'd by	**:** EvW	**Rev.**	**:** 01
Checked	**:**	**Date**	**:** 24-1-2020

Upheaval buckling calculation

Pipe data

	Formula	Symbol	Value	Unit
Outside pipe diameter		OD_s =	508	mm
Pipe wall thickness		t_s =	20.62	mm
Internal pipe diameter	$= OD\_s - 2 \cdot t\_s$	ID_s =	466.76	mm

Steel data

	Formula	Symbol	Value	Unit
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	$= \frac{1}{4} \cdot \pi \cdot \left(OD^2\_s - ID^2\_s\right)$	A_s =	31572.3	mm^2
Internal pipe area	$= \frac{1}{4} \cdot \pi \cdot ID^2\_s$	A_i =	1.71E+05	mm^2
Moment of inertia	$= \frac{\pi}{64} \cdot \left(OD^4\_s - ID^4\_s\right)$	I_s =	9.39E+08	mm^4
Pipe weight in air		W_{pe} =	247.8	kg/m
Sea water density		r_{sw} =	1025	kg/m^3
Pipeline contents density		r_{cont} =	88.7	kg/m^3

Internal lining

	Formula	Symbol	Value	Unit
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

	Formula	Symbol	Value	Unit
Thickness		t_{c1} =	3	mm
Density		ρ_{c1} =	930	kg/m^3
Layer 1 weight	$W_{l1} = \frac{\pi}{4} \cdot \left\{(OD + 2 \cdot t_{c1})^2 - OD^2\right\} \cdot \rho_{c1}$	W_{l1} =	4.5	kg/m

Weight piggy back line

	Formula	Symbol	Value	Unit
Piggy back weight		W_{l2} =	0.0	kg/m

Concrete coating

	Formula	Symbol	Value	Unit
Thickness		t_{con} =	0	mm
Density		ρ_{con} =	0	kg/m^3
Concrete weight	$W_{con} = \frac{\pi}{4} \cdot \left\{(OD + 2 \cdot t_{c1} + 2 \cdot t_{c2} + 2 \cdot t_{con})^2 - (OD + 2 \cdot t_{c1} + 2 \cdot t_{c2})^2\right\} \cdot \rho_{con}$	W_{con} =	0.0	kg/m

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Marine growth

Description	Formula	Symbol	Value	Unit
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

Description	Formula	Symbol	Value	Unit
Total outside diameter	$ODtot = OD + 2 \cdot t \cdot + 2 \cdot t_{c2} + 2 \cdot t_{con} + 2 \cdot t_{mg}$	OD_{tot} =	514.0	mm
Contents weight	$W_{cont} = \pi/4 \cdot (ID - 2 \cdot t_l)^2 \cdot \rho_{cont}$	W_{cont} =	15.2	kg/m
Pipeline weight in air	$w_r = w_{pe} + w_l + w_{l1} + w_{l2} + w_{con} + w_{mg} + w_{cont}$	W_r =	267.5	kg/m
Buoyancy force, F_B	$F_B = \pi/4 \cdot OD_{tot}^2 \cdot \rho_w$	F_B =	212.7	kg/m
Submerged pipeline weight, W_{sm}	$W_{sm} = W_r - F_B$	W_{sm} =	54.8	kg/m

Soil data

Description	Formula	Symbol	Value	Unit
Submerged soil cover density		γ' =	850	kg/m^3
Angle of internal friction		ϕ_{soil} =	28	deg.
Potyondy coeff. Soil		p_{soil} =	0.6	-
Height soil cover from top of pipe		Htop =	0.8	m
Height soil cover from center of pipe		H	1.06	
Soil uplift coefficient		f_{soil} =	0.1	-

(0.5 for dense materials and 0.1 for loose materials)

Description	Formula	Symbol	Value	Unit
Soil weight on top of pipe	$q = \gamma' \cdot H \cdot OD_{tot} \cdot (1 + f \cdot H / OD_{tot})$	q =	5461.9	N/m
Imperfection height		δ =	600	mm

Pressure data

Design pressure	P_d =	111	barg
Maximum operating pressure	P_i =	95	barg
Minimum external pressure	P_e =	1.01	barg

Temperature data

Seawater temperature, T_{sea}	T_{sea} =	3	^{o}C
Temperature of gas, T_{gas}	T_{gas} =	43	^{o}C

Pipeline forces

Description	Formula	Symbol	Value	Unit
Compressive temperature force, F_T	$F_T = E \cdot A \cdot \alpha \cdot (T_{gas} - T_{sea})$	F_T =	3043822.4	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 =	1283345.0	N
Compressive member end force, F_e	$F_e = \{P_D - P_e\} \cdot \pi/4 \cdot ID_s^2$	F_e =	1882123.1	N

Is area under considerations within anchor zone (y/n) ? = n

(y: F_T can be neglected)

Description	Formula	Symbol	Value	Unit
Effective compressive axial force, F_{eff}	$F_{eff} = F_T - F_P + F_e$	F_{eff} =	3642600.5	N

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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	2658.345	6000
2	0.274	0.0646	2658.345	6000
4	0.549	0.0646	2658.345	6000
6	0.823	0.0646	2658.345	6000
8	1.098	0.0646	2658.345	6000
10	1.372	0.0646	2658.345	6000
12	1.647	0.0646	2658.345	6000
14	1.921	0.0646	2658.345	6000
16	2.195	0.0646	2658.345	6000
18	2.470	0.0646	2658.345	6000
20	2.744	0.0646	2658.345	6000
22	3.019	0.0646	2658.345	6000
24	3.293	0.0646	2658.345	6000
26	3.568	0.0646	2658.345	6000
28	3.842	0.0646	2658.345	6000
30	4.117	0.0646	2658.345	6000
32	4.391	0.0646	2658.345	6000
34	4.665	0.0745	3064.458	6000
36	4.940	0.0844	3472.879	6000
38	5.214	0.0894	3678.596	6000
40	5.489	0.0912	3752.716	6000
42	5.763	0.0909	3741.640	6000
44	6.038	0.0893	3676.014	6000
46	6.312	0.0869	3576.265	6000
48	6.586	0.0840	3456.096	6000
50	6.861	0.0808	3324.726	6000
52	7.135	0.0775	3188.350	6000
54	7.410	0.0741	3051.110	6000

56	7.684	0.0709	2915.740	6000
58	7.959	0.0677	2784.008	6000
60	8.233	0.0670	2756.057	6000
62	8.507	0.0672	2763.740	6000
64	8.782	0.0668	2749.280	6000
66	9.056	0.0661	2718.373	6000
68	9.331	0.0650	2675.386	6000
70	9.605	0.0638	2623.669	6000
72	9.880	0.0624	2565.802	6000
74	10.154	0.0608	2503.772	6000
76	10.428	0.0593	2439.109	6000
78	10.703	0.0577	2372.987	6000
80	10.977	0.0560	2306.308	6000
82	11.252	0.0544	2239.758	6000
84	11.526	0.0528	2173.858	6000
86	11.801	0.0513	2108.996	6000
88	12.075	0.0497	2045.461	6000
90	12.350	0.0482	1983.458	6000
92	12.624	0.0467	1923.133	6000
94	12.898	0.0453	1864.581	6000
96	13.173	0.0439	1807.859	6000
98	13.447	0.0426	1752.995	6000
100	13.722	0.0413	1699.993	6000