CIVILS DESIGN
AND CONSTRUCT

SURFACE LOAD CALCULATIONS
HOUSING DEVELOPMENT SITE ACCESS
WHITE HOUSE FARM, TRUNCH
4½" STEEL HP GAS MAIN - STRUCTURAL ASSESSMENT

Client:	Tidswell Childs LLP
Design Required:	Surface Load Calculation
Contract Reference:	CDC-038

DESIGN REPORT

HOUSING DEVELOPMENT ACCESS ROAD
Ø4½" STEEL HP GAS MAIN
STRUCTURAL ASSESSMENT

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01	**Issued for Acceptance**	**Project Confidential**

Contents

1 Introduction

Tidswell Child LLP (hereby referred to as Client) are constructing an access road for a new housing development to the west of White House Farm, Mundesley Road, Trunch. The development is a single detached house, and the access will be used for both construction and permanent traffic. The access into the field that will be upgraded and used by the dwelling and the construction traffic during the build, passes over an existing High Pressure (HP) gas main.

Civils Design & Construct (herby referred to as CDC) have been appointed by the client to conduct an assessment of the proposed HP gas pipeline crossing, to assess whether or not the proposed crossing is acceptable with regards to the increased surcharge loads imposed by; vehicle movements, construction activities and increased surcharge. This report documents the proposed design and provides an assessment of the buried gas main to determine the suitability of the proposed crossing detail.

2 Crossing Location

The location of the proposed gas main crossing (including grid co-ordinates of the site) is detailed below, with the location shown in Figure 1 below, with supplementary drawings included in Appendix C.

- Address: White House Farm, Mundesley Road, Trunch, North Walsham NR28 0QB.
- Grid reference: E 628862, N 334871.

Figure 1 - Location of gas main crossing

3 Design Parameters

The available pipe data is included as Appendix D of this report, the information contained within this Appendix provides the inputs for the surcharge load assessment. These inputs are clearly presented in §2 of the surcharge load assessment (Appendix A) and summarised in Table 1 below. Where information is not available assumptions have been made based on guidance in the relevant industry standards.

Design Parameter	Value
Cadent Asset Identifier	PL1713-PTG-PLFL-1100PN
Pipe Reference	4.5" HP Steel Main
Pipe Material grade	X42
Pipe Outer Diameter	Ø114.3mm
Pipe wall thickness	6.02mm line pipe*1 / 11.91mm proximity pipe
Pipe Max Operating Pressure	19 barg
Pipe operational temperature range	Minimum temperature: +5°C (assumed) Maximum temperature: +20°C (assumed)
Pipe unpressurised temp range	Minimum tie-in temperature: +5°C (assumed) Maximum tie-in temperature: +15°C (assumed)
Traffic Loading	Loadings remote to a public highway as defined in BS EN 1991-2 (2003).
Cross Section (road thickness)	▪ 600mm 6F2/1 stone
Finished pipe cover to pipe crown (Appendix F)	▪ Minimum cover – 1.5m ▪ Maximum cover – 1.6m
Ground conditions (Appendix E)	Medium density sands and gravel Minimum CBR 4% (assumed)

Table 1 - Design Parameters

*1 Drawings contained within Appendix D indicate the crossing point is in the vicinity of both line & proximity pipe, hence 6.02mm WT has been used in the structural assessment (Appendix A)

4 Calculations

A detailed pipeline structural assessment is presented in Appendix A of this report, the assessment includes all necessary referencing, an assessment methodology and clearly details all assumptions and design inputs.

Only the temporary construction loadings were considered in this assessment. Traffic loadings will be assessed based on guidelines set out in BS EN 1991-2 (2003) and its National Annex. Loadings remote to a public highway (LM3) considered.

5 Summary

An evaluation was required to assess the proposed access road over an existing 4.5" HP gas main. The calculations attached in Appendix-A assessed the asset and proposed loadings to determine the increased pipe stresses subjected to the main. All input data together with detailed pipeline surcharge load calculations and a resultant stress analysis is contained within Appendix A.

Using all available information provided by the client and Cadent, in accordance with industry best practise and relevant specifications, as referenced in section 2 of Appendix A, this study finds that the proposed crossing point is acceptable and the resultant pipeline stresses are within the allowable pipeline limits as detailed in Appendix A.

Appendices Section

Appendix A - Calculations

§1.1 Introduction

These calculations show the method used to assess the surcharge loadings on an existing gas pipeline. The assessment has been carried out with respect to Cadent apparatus and have been checked and approved in accordance with industry best practise. These calculations should not be used or relied upon for any purpose other than for which they have been provided. CDC shall not be liable for any use of the information by any third party for any purpose other than which they were originally prepaired.

§1.2 Assessment Methodology

The pipeline assessment involves th calcultion of effective vehicle surcharges to be considered in a pipe stress analysis along with other relevant design actions including pipeline pressure, temperature range, and soil load. The calculation of the transient earth pressures due to vehicle loading is based on Boussinesq theory for load dispersal. Calculations for the effects of vehicle and other actions will be by theory set out in NEN3650 [Ref 3] (for determining circumferential bending stresses) and the stress criteria in GD/SP/GM/1 [Ref 2] will govern.

The following assumptions have been made in the design process:

- This assessment considers the expected traffic loadings as defined in BS EN 1991-2 [Ref 1] using the guidiance of GM1 [Ref 2].
- The benefit of load spread or load-relieving influence from the makeup of the road construction has been considered in this assessment.
- Load dispersal through overburden is determined based on Boussinesq theory.
- Soil surcharge loading is based on the most onerous effective earth pressures based on initial consolidation and compaction of the backfill for a pipeline installed in a trench.
- Groundwater has the effect of reducing net vertical pipe loading, therefore for determining pipe stresses it has been omitted.
- There is no requirement for a corrosion allowance or pre-existing fatigue damage in the stress analysis calculations.
- A design factor of 0.72 applicable for cross country pipelines for hoop stress criteria is appropriate.
- Pipeline manufacturing tolerances have been considered as calculated in §3 below.
- This assessment does not assess the integrity of the proposed road surface and general construction. The subsoil has been assumed to have a minimum CBR of 4% which will need to be assessed on site during construction.

§1.3 Issue History

Issue 01 - Dated 30/01/2021 - Issued for review.

For any information pertaining to the contents of this report please contact: civils@designandconstructltd.com

§1.4 References

[1] BS EN 1991-2 (2003). Eurocode 1: Actions on structures - Part 2: Traffic Loads on bridges.

[2] GD/SP/GM/1 (2019). Cadent specification for: The protection of pipelines from ground movement and external loadings - External loading on steel pipelines and buried pipeline installations.

[3] NEN 3650 (2020). Requirements for pipeline systems. Part 1: General

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[7] GD/SP/CE/12 (2019). National Grid specification for: The design, construction and testing of civil and structural works. Part 12: Protection works over steel pipelines.

[8] GD/PM/P/18 (2019). Management procedure for working on pipelines containing defective girth welds or girth welds of unknown quality.

[9] API 5L (2004). Specification for Line Pipe. Steel Pipelines.

[10] DNV (1992). Foundations. Clasification notes no 30.4.

[11] BS EN 1555-2 (2002). Plastics piping systems for the supply of gaseous fuels - Polyethylene (PE) - Part 2

[12] Pipelife Norge AS (2002). Technical catalogue for the installation of PE pipes.

[13] Busby, J. (2015). UK shallow ground temperatures for ground coupled heat exchangers. *Quarterly Journal of Engineering Geology and Hydrogeology*, 48(3-4), pp.248-260.

[14] IGEM (2005). TD_3 Edition 4 - Steel and PE pipelines for gas distribution

[15] BS EN 1295 (1997) Structural design of buried pipelines under various conditions of loading — Part 1 General requirements

[16] BS EN 9295 (2010) Guide to the structural design of buried pipelines.

[17] Gas industry standard (2006). GIS_L2. Steel pipe 21.3mm to 1219mm outside diameter for operating pressures up to 7 bar.

[18] Gas industry standard (2016). GIS_PL2. Polyethylene pipes and fittings for natural gas and suitable manufactured gas.

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[20] PD 8010 (2015). Specification for steel pipelines on land.

[21] IGE/TD/1 (2009). TD_1 Edition 5 - Steel pipeline and associated installations for high pressure gas transmissions.

[22] NEN 3650 (2020). Requirements for pipeline systems. Part 2: Steel Pipelines

[23] NEN 3650 (2020). Requirements for pipeline systems. Part 3: Plastic Pipelines

[24] NEN 3650 (2020). Requirements for pipeline systems. Part 4: Cast Iron Pipelines

[25] ASME B31.8 (2018). Gas Transmission & Distribution Piping Systems

[26] GD/SP/GM/4 (2019): Specification for the Protection of Steel Pipelines Operating at Pressures above 7 Bar Subjected to Vibrations Caused by Blasting, Piling or Demolition

§2 Input Data

The information below has been used as input data for the surcharge load assessment. Where relevant information has been provided by the client or asset owner this is included in Appendix D, where values have been assumed it is clearly stated in the main body of the report.

§2.1 Pipeline Parameters

Pipe OD	$OD_{pipe} := 4.5\ in$	$OD_{pipe} = 114.3\ mm$
Pipe wall thickness	$th_{pipe} := 6.02\ mm$	
Pipe internal diameter	$ID_{pipe} := OD_{pipe} - 2 \cdot th_{pipe}$	$ID_{pipe} = 102.26\ mm$

Steel pipeline - Above 7 bar

Steel grade - X42 [9]

Manufacturing tol, pipe OD - [9] Table 7	$\chi D_{min} := -1\% \cdot OD_{pipe}$	$\chi D_{min} = -1.14\ mm$
	$\chi D_{max} := 1\% \cdot OD_{pipe}$	$\chi D_{max} = 1.14\ mm$
Manufacturing tol, pipe th - [9] Table 9	$\chi th_{min} := -12.5\% \cdot th_{pipe}$	$\chi th_{min} = -0.75\ mm$
	$\chi th_{max} := 15\% \cdot th_{pipe}$	$\chi th_{max} = 0.9\ mm$
	$th_{nom} := th_{pipe}$	$th_{nom} = 6.02\ mm$
Maximum factory out-of-roundness	$\delta_{tol} := 0.02 \cdot OD_{pipe}$	$\delta_{tol} = 2.29\ mm$
Tensile yeild strength - [18] Table 6	$\varepsilon_{smys} := 290\ MPa$	
Elastic modulus - short term	$E_s := 210\ GPa$	
Elastic modulus - long term	$E := 210\ GPa$	
Poissons ratio of steel	$\nu := 0.3$	
Coefficient of linear expansion of steel	$\alpha_g := 1.17 \cdot 10^{-5}\ m \cdot (m \cdot K)^{-1}$	
Density of steel	$\gamma_{pipe} := 7850\ kg \cdot m^{-3} \cdot g$	
Density of pipe coating (3LPP)	$\gamma_{coat} := 795\ kg \cdot m^{-3} \cdot g$	
Pipe coating thickness - Assumed	$th_{coat} := 0.3\ \mu m$	
Minimum bend radius of pipe Note, R=1000m if no forged bend	$R_{bend} := 3 \cdot OD_{pipe}$	

§2.2 Pipeline Operating Conditions

Pipeline maximum operating pressure $\rho := 19\ bar$

Pipeline test pressure (Assumed) $\rho' := \rho \cdot 1.5$ $\rho' = 28.5\ bar$

Pipeline classification Pipe = "High pressure pipeline"

Density of water $\gamma_w := 1000\ kg \cdot m^{-3} \cdot g$

Density of natural gas $\gamma_{gas} := 0.9\ kg \cdot m^{-3} \cdot g$

Design factor for test conditions (Steel pipes) - [11] §8.2.3 $f := 1.05$

Theoretical test limit - [11] §8.2.4 $Z := \dfrac{2 \cdot th_{pipe} \cdot \varepsilon_{smys} \cdot f}{OD_{pipe}}$ $Z = 321\ bar$

Pipe Temperature temperatures - [2] §5.3.3.6 / [17] Table B.2

Min / max tie-in temperature $T_1 := -10\ °C$ $T_2 := 10\ °C$

Min / max operational temperature $T_3 := 5\ °C$ $T_4 := 20\ °C$

Min / max ground temperature - [13] Fig.1 $T_5 := 5\ °C$ $T_6 := 15\ °C$

§2.3 Ground water

Groundwater has the effect of reducing net vertical pipe loading, therefore for the purposes of determining pipe stresses it has been omitted.

Height of water table above pipe invert $H_{3'} := 0\ m$

§2.4 Ground Conditions

The relevant ground investigation information is attached in E of this report. Where appropriate this analysis has based the soil parameters on a native soil composition of a; medium density sands and gravels. This soil comoposition has been inferred from the GI presented in Appendix E. Assumed / inferred ground conditions as follows.

Please note: *Ground investigation information contained within this assessement is included in E of the report.*

Minimum subsoil CBR	$CBR := 4\%$
Assumed soil density in BS1295 - [15] NA.4.3.1	$\gamma_{soil} := 19\ kN \cdot m^{-3}$
Estimated undrained soil shear strength	$c_u := 10\ kPa$
Angle of internal friction - [3] §B.4.1	$\phi := 32.5\ deg$
Effective cohession - [3] §B.4.1	$c' := 2\ MPa$
E modulus of subsoil - [3] §B.4.1	$E' := 10\ MPa$
Ku - [15] NA.4.3.1	$K_\mu := 0.19$
Ku - [15] NA.4.3.1	$K_{\mu'} := 0.13$

Load displacement constants (k-values) - [3] Table C.6

Compacted trench backfill of normal sand and a pipe outer diameter of 100mm with 1m of soil cover.

Natural soil compaction percentage (compacted stiff clay) - [3] §C4.2.3	$\mu_{un} := 2\%$	
Minimum modulus sub-grade vertical reaction - [3] Table C.6	$k_{v\_min} := 0.045 \cdot 100\ N \cdot mm^{-3}$	
Average modulus sub-grade vertical reaction - [3] Table C.6	$k_{v\_av} := 0.11 \cdot 100\ N \cdot mm^{-3}$	
Minimum vertical k-value - [3] Table C.6	$k_h := 0.028 \cdot 100\ N \cdot mm^{-3}$	
Poissons Ratio of sub-grade (6F5)	$\upsilon_{6F5} := 0.25$	
Trench width - [15] Assumed to be equal to width of pipeline (conservative)	$B_d := OD_{pipe}$	$B_d = 114.3\ mm$

Flexible and semi-rigid pipe embedment properties [15]

Embeddment Class - [16] Table B.3	Class: **S3**
Spangler Modulus - [15] Table NA.1	$E'_3 := 9\ MN \cdot m^{-2}$
Compaction Class - [15] Table NA.6	Class: **90%**
Deflection coefficent - [15] Table NA.6	$K_x := 0.10$
Modulus of soil reaction - [15] Table NA.6	$E'_2 := 7\ MN \cdot m^{-2}$
Deflection Lag Factor - [15] Table NA.6	$D_L := 1.25$
Strain Factor - [15] Table NA.6	$D_F := 4.25$

§2.5 Pipe cover

Pre-construction cover

Maximum pipe cover - Existing ground level to pipe crown	$H_{max} := 1.6\ m$
Minimum pipe cover - Ground level to pipe crown	$H_{min} := 1.5\ m$

§2.6 Perminant road crossing point

The road cross section is shown in Appendix C and summarised below:

Finsished site ground level	$\Delta_h := 0\ m$	
Resultant cover - perminant crossing point	$H_{min'} := H_{min} + \Delta_h$	$H_{min'} = 1.5\ m$

§2.6.1 Road construction detail

The road cross section is shown in Appendix C and summarised below:

Number of notional lanes	$n_l := 1$
Carriageway width	$w := 4\ m$

Surface course (AC-20) depth	$h_1 := 0\ mm$	
Base (Type 1) depth	$h_2 := 0\ mm$	
Sub babse (6F5) depth	$h_3 := 600\ mm$	
Road cross sectional above pipe	$H_{road} := h_1 + h_2 + h_3$	$H_{road} = 600\ mm$
General fill course thickness	$H_{soil} := H_{min'} - H_{road}$	$H_{soil} = 900\ mm$
Surface course (C50) density	$\gamma_1 := 2500\ kg \cdot m^{-3} \cdot g$	
Base course (Type 1) density	$\gamma_2 := 1900\ kg \cdot m^{-3} \cdot g$	
Base course (6F5) density	$\gamma_3 := 1900\ kg \cdot m^{-3} \cdot g$	
Composite road density	$\gamma_{road} := \dfrac{\gamma_1 \cdot h_1 + \gamma_2 \cdot h_2 + \gamma_3 \cdot h_3}{H_{road}}$	$\gamma_{road} = 1900\ kg \cdot m^{-3} \cdot g$

§2.4.1 Allowances for load spreading - Fictional depth of cover - FINISHED COVER

NEN 3650-1:2003 - Ref [3] §C.5.2 - Contains guidance for the load-relieving infludence of road construction. The effect of which has been calculated below.

Load-relieving factor - Sand cement - Ref [3] Table C.9 $\beta_a := 0.939$

Load-relieving factor - Crushed Stone - Ref [3] Table C.9 $\beta_b := 0.134$

Equivilant depth of cover (finished) - Ref [3] §C.5.2 $H_{eq} := H_{min'} + \beta_a \cdot (h_1 + h_2 + h_3)$ $H_{eq} = 2063.4\ mm$

Equivilant depth to centre of pipe axis $H_1 := H_{eq} + 0.5 \cdot OD_{pipe}$ $H_1 = 2120.55\ mm$

§2.4.1 Allowances for load spreading - Fictional depth of cover - TEMPORARY COVER (Laying sub-base)

Equivilant height is calculated with minimimal sub-base cover for the first roller pass during construction.

Sub-base lift height $H_{sub} := 300\ mm$

Equivilant depth of cover (temperoray construction case) - Ref [3] §C.5.2 $H_{eq'} := H_{soil} + \beta_b \cdot (H_{sub})$ $H_{eq'} = 0.94\ m$

Equivilant depth to centre of pipe axis $H_{1'} := H_{eq'} + 0.5 \cdot OD_{pipe}$ $H_{1'} = 997.35\ mm$

§3 Pipe Geometry

Throughout the proceeding analyses allowances have been made for appropriate manufacturing tolerances as defined in §2.1. The appropriate maximum or minimum geometrical values have been used to ensure the most onerous pipe case is considered in the structural assessment of the pipeline, ensuring the analysis is conservative in its approach. As a general rule the maximum pipe outer diameter, corresponding with the minimum pipe thickness (inclusive of manufacturing tolerances), generate the most onerous condition for the structural analyses and this case has been assumed throughout the assesssment unless instructed otherwise by relevant specifications (referenced accordingly).

Pipe outer diameter - including manufacturing tolerances as defined in §2.1

Max pipe OD (exc. coating)	$OD_{max} := OD_{pipe} + \chi D_{max}$	$OD_{max} = 115.44\ mm$
Min pipe OD (exc. coating)	$OD_{min} := OD_{pipe} + \chi D_{min}$	$OD_{min} = 113.16\ mm$
Max pipe OD (inc. coating)	$OD_{tot} := OD_{max} + 2 \cdot th_{coat}$	$OD_{tot} = 115.44\ mm$

Pipe thickness - including manufacturing tolerances as as defined in §2.1

Max pipe thickness	$th_{max} := th_{pipe} + \chi th_{max}$	$th_{max} = 6.92\ mm$
Min pipe thickness	$th_{min} := th_{pipe} + \chi th_{min}$	$th_{min} = 5.27\ mm$
Av pipe thickness	$th_{pipe} := (th_{max} + th_{min}) \cdot 0.5$	$th_{pipe} = 6.1\ mm$
Average diameter - [3] §D.1.1	$D_g := OD_{max} - th_{min}$	$D_g = 110.18\ mm$

Pipe internal diameter

Maximum	$ID_{max} := OD_{max} - 2 \cdot th_{pipe}$	$ID_{max} = 103.25\ mm$
Mininimum	$ID_{min} := OD_{min} - 2 \cdot th_{pipe}$	$ID_{min} = 100.97\ mm$

Pipe radius - including manufacturing tolerances as as defined in §2.1

Max outer radius (inc. coating)	$R_{max} := 0.5 \cdot OD_{tot}$	$R_{max} = 57.72\ mm$
Min inner radius	$R_{min} := 0.5 \cdot ID_{min}$	$R_{min} = 50.48\ mm$
Average pipe radius - [3]	$R_g := 0.5 \cdot (R_{max} + R_{min})$	$R_g = 54.1\ mm$
Pipe cross sectional area (exc. coating)	$A_{max} := \pi \cdot \left(\left(\frac{OD_{max}}{2} \right)^2 - \left(\frac{OD_{max} - 2 \cdot th_{pipe}}{2} \right)^2 \right)$	$A_{max} = 2093.88\ mm^2$
Pipe second moment of area (y-axis) - [4]	$I_{y\_max} := \frac{\pi \cdot \left(OD_{pipe}^{\ 4} - (OD_{pipe} - 2 \cdot th_{pipe})^4 \right)}{64}$	$I_{y\_max} = (3.04 \cdot 10^6)\ mm^4$
Pipe wall second moment of area (y-axis) - [4]	$I_w := \frac{th_{pipe}^{\ 3}}{12}$	$I_w = (1.89 \cdot 10^{-8})\ m^3$
Wall modulus - [4]	$W_w := \frac{th_{pipe}^{\ 2} \cdot mm}{6}$	$W_w = 6.19\ mm^3$
Pipe Stiffness	$P_s := \frac{E \cdot I_{y\_max}}{0.149 \cdot \left(\frac{OD_{pipe}}{2} \right)^3 \cdot m}$	$P_s = 22.97\ GPa$

§4 Surcharge Loadings (LM3 loadcase, single passing lane)

Surcharge loadings are calucated in the following section, with multiple applicable cases considered .

§4.1 Traffic loadings (Ref [1] - BS EN 1991-2)

Traffic loadings are taken in accordance with T/SP/CE/12 (Ref [7] §5.2) and BS EN 1991-2 (Ref [1] §4.3).

As per GM1; the pipleine has been classified as "remote from a public highway" consequently loading is subject to to vehicles that are permitted to use the highway without special authorisation, 0.685 x LM3 (based on SV100 vehicles), with a corrisponding a maximum axle load of 114kN. This loadcase is assessed below with an appropriate DAF applied:

Calculated equivilant minimum depth of cover (not allowing for load spread distribution)	$H_1 := H_{min}$	$H_1 = 1.5\ m$

§4.1.1 Resultant pipe stresses

Load model 3 - LM3 [1] §4.3.4 & NA.2.16.1.3 (Figure NA.1.b)

Impact factor - [1] Table NA.2	$\alpha_{DAF} := 2$	
No. axles considered	$n := 6$	
Axle width	$a_1 := 3\ m$	
Wheel spacing	$a_3 := 1.2\ m$	
	$a_{3'} := 2\ m$	
Road width	$w := 3.5\ m$	
Wheel contact length	$A := 350\ mm$	
Wheel contact width	$B := 350\ mm$	
Contact area	$AB := A \cdot B$	$AB = 0.12\ m^2$
Axle load (SV100 vehicles)	$Q_{SV100} := 0.685 \cdot 17\ tonne \cdot g$	$Q_{SV100} = 114.2\ kN$
Axle load (including DAF)	$Q_{LM3} := Q_{SV100}$	$Q_{LM3} = 114.2\ kN$
Wheel load	$Q_{LM3'} := 0.5 \cdot Q_{LM3}$	$Q_{LM3'} = 57.1\ kN$
Resulant bearing stress	$q_{LM3} := \dfrac{Q_{LM3'}}{AB}$	$q_{LM3} = 466.12\ kPa$
Disperal angle of concentrated loads - [1] §4.3.6	$\theta := 45\ deg$	
Road depth	$H_{road} = 600\ mm$	
Disperal of load	$x := H_{road} \cdot (\tan(\theta))$	$x = 0.6\ m$
Subsoil bearing surface	$AB' := (2 \cdot x + A) \cdot (2 \cdot x + B)$	$AB' = 2.4\ m^2$
Resultant bearing pressure on subsoil	$q_{res} := \dfrac{Q_{LM3'}}{AB'}$	$q_{res} = 23.77\ kPa$
Bearing capacity factor - [5] §8.4.2	$N_c := 5.14$	
Shape factor - [5] §8.4.2	$S_c := 1 + 0.2 \cdot \left(\dfrac{A}{B}\right)$	$S_c = 1.2$
Bearing capacity - [5] §8.4.2	$q_{ult} := c_u \cdot N_c \cdot S_c$	$q_{ult} = 61.68\ kPa$

Bearing capacity safety factor $\chi_b := 2$

Bearing capacity utilitisation $UTL_{qult} := \frac{\chi_b \cdot q_{res}}{q_{ult}}$ $UTL_{qult} = 0.77$

Resultant normal pipe stresses

The maximum resultant normal stress acting on the pipe is calculated using Boussinesq Equation [Ref 5 - Pg 336]. The load is calculated assuming a maximum axle weight of 114kNis applied to three individual axles, each at 1.2m spacing.

Corresponding arc distances for each of the 12 wheels (6 axles) are calculated below:

$R_1 := \sqrt{H_1^2 + (2 \cdot a_3)^2}$ $R_1 = 2.83\ m$ $R_{1'} := \sqrt{H_1^2 + (2 \cdot a_3)^2 + a_1^2}$ $R_{1'} = 4.12\ m$

$R_2 := \sqrt{H_1^2 + a_3^2}$ $R_2 = 1.92\ m$ $R_{2'} := \sqrt{H_1^2 + a_3^2 + a_1^2}$ $R_{2'} = 3.56\ m$

$R_3 := \sqrt{H_1^2}$ $R_3 = 1.5\ m$ $R_{3'} := \sqrt{H_1^2 + a_1^2}$ $R_{3'} = 3.35\ m$

$R_4 := \sqrt{H_1^2 + a_{3'}^2}$ $R_4 = 2.5\ m$ $R_{4'} := \sqrt{H_1^2 + a_{3'}^2 + a_1^2}$ $R_{4'} = 3.91\ m$

$R_5 := \sqrt{H_1^2 + (a_{3'} + a_3)^2}$ $R_5 = 3.53\ m$ $R_{5'} := \sqrt{H_1^2 + (a_{3'} + a_3)^2 + a_1^2}$ $R_{5'} = 4.64\ m$

$R_6 := \sqrt{H_1^2 + (a_{3'} + 2 \cdot a_3)^2}$ $R_6 = 4.65\ m$ $R_{6'} := \sqrt{H_1^2 + (a_{3'} + 2 \cdot a_3)^2 + a_1^2}$ $R_{6'} = 5.53\ m$

Maximum normal stress resulting from each of the 12 wheels (6 axles) are calculated below:

$q_1 := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_1^5}$ $q_2 := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_2^5}$ $q_3 := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_3^5}$ $q_4 := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_4^5}$ $q_5 := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_5^5}$

$q_1 = 0.51\ kPa$ $q_2 = 3.52\ kPa$ $q_3 = 12.12\ kPa$ $q_4 = 0.94\ kPa$ $q_5 = 0.17\ kPa$

$q_{1'} := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_{1'}^5}$ $q_{2'} := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_{2'}^5}$ $q_{3'} := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_{3'}^5}$ $q_{4'} := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_{4'}^5}$ $q_{5'} := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_{5'}^5}$

$q_{1'} = 0.08\ kPa$ $q_{2'} = 0.16\ kPa$ $q_{3'} = 0.22\ kPa$ $q_{4'} = 0.1\ kPa$ $q_{5'} = 0.04\ kPa$

$q_6 := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_6^5}$ $q_6 = 0.04\ kPa$ $q_{6'} := \frac{3 \cdot Q_{LM3'} \cdot H_1^3}{2 \cdot \pi \cdot R_6^5}$ $q_{6'} = 0.04\ kPa$

Resultant vertical traffic loading (vehicle 1)

$q_v := (q_1 + q_2 + q_3 + q_4 + q_5 + q_6 + q_{1'} + q_{2'} + q_{3'} + q_{4'} + q_{5'} + q_{6'}) \cdot \alpha_{DAF}$

$q_v = 35.87\ kPa$

Traffic load per unit length - [3] §C.5.1

$Q_v := q_v \cdot OD_{pipe}$

$Q_v = 4.1\ kN \cdot m^{-1}$

§4 Surcharge Loadings - CONSTRUCTION VEHICLES

Construction traffic - ROLLER LOADINGS

§4.1 Traffic loadings (Ref [1] - BS EN 1991-2)

Construction loading based on a maximum gross vehicle weight of a Roller, the Bomag BW 120 AD-5; gross vehicle weight of 3650kg. The stress has been calculated for the first subase layer, which is the critical load case.

Minimum height differntial from sub-base level to pipe — $H_{1'} := H_{soil}$

§5.1.1 Resultant pipe stresses

Max vehicle weight — $Q_{tot} := 3650\ kg \cdot g$ — $Q_{tot} = 35.79\ kN$

Number of axles — $n := 2$

Axle load — $Q_1 := \frac{Q_{tot}}{n}$ — $Q_1 = 17.9\ kN$

Roller OD — $d_1 := 4900\ mm$

Roller length — $l_1 := 1200\ mm$

Roller length — $S_1 := 1752\ mm$

Roller poissons ratio — $v_1 := 0.3$

Roller youngs modulus — $E_1 := 7850\ MPa$

Sub-base poissons ratio — $v_2 := 0.25$

Sub-base youngs modulus — $E_2 := 10\ MPa$

Contact half width (Hertzian contact stresses - Shingley's) — $b_1 := \left(\frac{2 \cdot Q_1}{\pi \cdot l_1}\right) \cdot \frac{\left(\frac{1 - v_1^{\,2}}{E_1}\right) + \left(\frac{1 - v_2^{\,2}}{E_2}\right)}{\frac{1}{d_1}}$ — $b_1 = 4367.03\ mm^2$

Resultant Bearing Stress — $q_{max} := \frac{2 \cdot Q_1}{b_1}$ — $q_{max} = 8.2\ MPa$

Disperal angle of concentrated loads - [1] §4.3.6 — $\theta := 45\ deg$

Sub-base lift height — $H_{sub} = 300\ mm$

Disperal of load — $x := H_{sub} \cdot (\tan(\theta))$ — $x = 0.3\ m$

Subsoil bearing surface — $AB' := (2 \cdot x) \cdot l_1 + b_1$ — $AB' = 0.72\ m^2$

Resultant bearing pressure on subsoil — $q_{res} := \frac{Q_1}{AB'}$ — $q_{res} = 24.71\ kPa$

Bearing capacity factor - [5] §8.4.2 — $N_c := 5.14$

Shape factor - [5] §8.4.2 $S_c := 1 + 0.2 \cdot \left(\frac{A}{B}\right)$ $S_c = 1.2$

Bearing capacity - [5] §8.4.2 $q_{ult} := c_u \cdot N_c \cdot S_c$ $q_{ult} = 61.68\ kPa$

Bearing capacity utilitisation $UTL_{qult'} := \frac{q_{res}}{q_{ult}}$ $UTL_{qult'} = 0.4$

Bearing capacity safety factor $\chi_b := 2$

$Check_{bearing} :=$ if $UTL_{qult'} \cdot \chi_b \le 1$ return "Acceptable"; return "Artifical backfill required" = "Acceptable"

The CBR should be checked onsite and if the CBR is less than 4% a minimum thickness of 100mm of artical backfill will be required as a base layer.

Resultant normal pipe stresses

The maximum resultant normal stress acting on the pipe is calculated using Boussinesq Equation [Ref 5 - Pg 336]. The load is calculated assuming a maximum vehicle weight of 3,650kg distributed over two rollers.

$R_1 := \sqrt{H_1^2}$ $R_1 = 1.5\ m$ $R_{1'} := \sqrt{H_1^2 + S_1^2}$ $R_{1'} = 2.31\ m$

Maximum normal stress resulting from each of the rollers are calculated below:

$q_1 := \frac{3 \cdot Q_1 \cdot H_1^3}{2 \cdot \pi \cdot R_1^5}$ $q_2 := \frac{3 \cdot Q_1 \cdot H_1^3}{2 \cdot \pi \cdot R_2^5}$

$q_1 = 3.8\ kPa$ $q_2 = 1.1\ kPa$

Resultant vertical traffic loading (vehicle 1) $q_{vc'} := (q_1 + q_2) \cdot \alpha_{DAF}$

$q_{vc'} = 9.8\ kPa$

Surcharge load per unit length - [3] §C.5.1 $Q_{vc'} := q_{vc'} \cdot OD_{pipe}$ $Q_{vc'} = 1.12\ kN \cdot m^{-1}$

Critical load case - the critical loadcase is calculated below, with the maximum used throughout the assesment

Resultant vertical traffic loading (vehicle 1)

$q_v := \max(q_{vc'}, q_v)$

$q_v = 35.87\ kPa$ $\qquad$ $q_v = 35.87\ kN \cdot m^{-2}$

Traffic load per unit length - [3] §C.5.1

$Q_v := q_v \cdot OD_{pipe}$ $\qquad$ $Q_v = 4.1\ kN \cdot m^{-1}$

Maximum vehicle loading

$q_{res'} := Q_{LM3}$ $\qquad$ $q_{res'} = 114.2\ kN$

Maximum resultant varible pressure

$q_{res''} := q_v$ $\qquad$ $q_{res''} = 35.87\ \frac{kN}{m^2}$

§5 Soil Modulus reaction factors - Flexible / Semi Rigid Pipes

Soil modulus adjustment factor - [15] §NA.5.2.2

$$C_L := \frac{0.985 + \left(0.544 \cdot \frac{B_d}{OD_{pipe}}\right)}{\left(1.985 - 0.456 \cdot \left(\frac{B_d}{OD_{pipe}}\right)\right) \cdot \left(\frac{E'_2}{E'_3}\right) - \left(1 - \left(\frac{B_d}{OD_{pipe}}\right)\right)}$$

$$C_L = 1.29$$

Overall modulus of soil reaction [15] §NA.5.2.2

$$E'' := \min\left(E'_2 \cdot C_L, E'_2\right) \qquad E'' = 7000\ kPa$$

Pipe-soil stiffness factor [2] §4.1.2

$$\eta := \frac{\left(\frac{E''}{D_L}\right)}{\left(\frac{105 \cdot E \cdot I_w}{OD_{pipe}^{\ 3}}\right) + \left(\frac{0.8 \cdot E''}{D_L}\right)} \qquad \eta = 0.02$$

§5.1 Soil Loading as per NEN3650

Pipe soil cover

$$H_{soil} = 900\ mm$$

Coefficient for calculating the soil load according to Marston - [3] § C.4.2.4.2

$$f_m := 0.3$$

Neutral soil pressure - [3] § C.4.2.2

$$q_n := H_{soil} \cdot \gamma_{soil} \qquad q_n = 17.1\ kN \cdot m^{-2}$$

Neutral soil load - [3] § C.4.2.2

$$Q_n := H_{soil} \cdot \gamma_{soil} \cdot OD_{tot} \qquad Q_n = 1.97\ kN \cdot m^{-1}$$

Vertical passive soil pressure - [3] § C.4.2.4.2

$$q_p := q_n \cdot \left(1 + f_m \cdot \left(\frac{H_{soil}}{OD_{tot}}\right)\right) \qquad q_p = 57.09\ kN \cdot m^{-2}$$

Vertical modulus of subgrade reaction (Clay / Peat) - [3] § C.4.3.2

$$z_1 := 0.25 \cdot \frac{OD_{tot}}{\left(\frac{E'}{MPa}\right)^{1.5} \cdot \sqrt{\frac{H_{soil}}{OD_{tot}}}} \qquad z_1 = 0.33\ mm$$

Vertical modulus of subgrade reaction (Sand) - [3] § C.4.3.2

$$z_1 := 0.2 \cdot \frac{OD_{tot}}{\left(\frac{E'}{MPa}\right)^{0.5} \cdot \sqrt{\frac{H_{soil}}{OD_{tot}}}} \qquad z_1 = 2.61\ mm$$

Load displacement constant (top) [3] § C.4.3.2

$$k_{vtop} := \frac{q_p - q_n}{z_1} \qquad k_{vtop} = \left(1.53 \cdot 10^{-2}\right)\ N \cdot mm^{-3}$$

Effective soil pressure - [3] § C.4.2.3

$$q_{k\_min} := \frac{q_n + \frac{\mu_{un} \cdot OD_{tot}}{z_1} \cdot \left(q_p - q_n\right)}{1 + \frac{q_p - q_n}{z_1 \cdot k_{v\_min}}} \qquad q_{k\_av} := \frac{q_n + \frac{\mu_{un} \cdot OD_{tot}}{z_1} \cdot \left(q_p - q_n\right)}{1 + \frac{q_p - q_n}{z_1 \cdot k_{v\_av}}}$$

$$q_{k\_min} = 52.23\ kN \cdot m^{-2} \qquad q_{k\_av} = 52.34\ kN \cdot m^{-2}$$

$$q_k := \max\left(q_{k\_min}, q_{k\_av}\right) \qquad q_k = 52.34\ kN \cdot m^{-2}$$

§5.2 Additional surcharge from pipe self weight

Pipe unit weight $Q_{pipe} := \gamma_{pipe} \cdot A_{max}$ $Q_{pipe} = 0.16\ kN \cdot m^{-1}$

Pipe coating weight $Q_{coat} := \pi \cdot \left(\left(\frac{OD_{tot}}{2} \right)^2 - \left(\frac{OD_{max} - 2 \cdot th_{coat}}{2} \right)^2 \right) \cdot \gamma_{coat}$

$Q_{coat} = 0\ kN \cdot m^{-1}$

Pipe contents weight $Q_{con} := \gamma_{gas} \cdot \pi \cdot \pi \cdot \left(\frac{ID_{max}}{2} \right)^2$ $Q_{con} = 0\ kN \cdot m^{-1}$

Pipe weight $Q_{eg} := Q_{pipe} + Q_{coat} + Q_{con}$ $Q_{eg} = 0.16\ kN \cdot m^{-1}$

Pipe buoyancy $Q_{op} := \text{if } H_{3'} > OD_{max} \;\; \| \; OD_{max}^{\;2} \cdot \gamma_w \cdot \frac{\pi}{4} \;\; \text{else} \;\; \| \; OD_{max} \cdot \gamma_w \cdot H_{3'}$ $Q_{op} = 0\ kN \cdot m^{-1}$

Vertical surcharge loading from pipe self weight $Q_{pipe} := Q_{eg} - Q_{op}$ $Q_{pipe} = 161.43\ N \cdot m^{-1}$

Floatation check $Check_{Float} := \| \text{ if } OD_{max}^{\;2} \cdot \gamma_w \cdot \frac{\pi}{4} < Q_k + Q_{pipe} \;\; \| \text{ return "Pipe does not float"} \;\; \text{return "Pipe floats"}$ = "Pipe does not float"

§5.3 Additional surcharge from road construction

Vertical surcharge loading from road cross section - [3] § C.4.2.2	$Q_{rc} := H_{road} \cdot (\gamma_{road}) \cdot OD_{pipe}$	$Q_{rc} = 1.28\ kN \cdot m^{-1}$

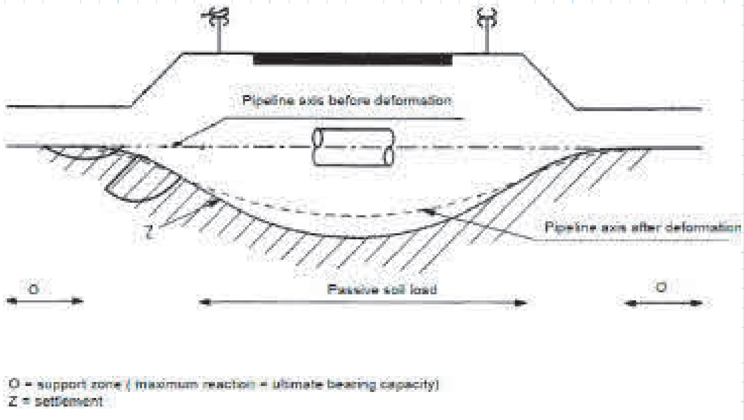
§5.4 Directly transfered total load - [3] §D.3.3

Perminant surcharge load	$Q_{nr} := Q_k + Q_{rc} + Q_{pipe}$	$Q_{nr} = 3.39\ kN \cdot m^{-1}$
Total vertical surcharge load	$Q_{tot} := Q_{nr} + Q_v$	$Q_{tot} = 7.49\ kN \cdot m^{-1}$
Effective stress	$\sigma'_0 := Q_{tot} \cdot OD_{pipe}^{-1}$	$\sigma'_0 = 65.56\ kPa$
Axial pipe load	$q_{tot} := Q_{tot}\ mm$	$q_{tot} = 7.49\ N$
Vertical Soil Pressure	$P_e := Q_{nr} \cdot OD_{pipe}^{-1}$	$P_e = 29.69\ kPa$
Surcharge Pressure	$P_s := Q_v \cdot OD_{pipe}^{-1}$	$P_s = 35.87\ kPa$

§6.1 Pipe stresses induced during trenching operations - [2] §5.3.3.8

During pipelaying operations stresses can be induced in the pipeline for a variety of reasons, most notably due to uneven trench bottom or the presence of rock on the bed of trench. GD/SP/GM/1 [Ref. 2] §5.3.3.8 states that these stress should be considered in the pipe stress analysis, hence these stresses are estimated below.

NEN 3850 [Ref. 3] §C.4.1.2 onsiders this loading case and models the pipeline as a beam in the case of settlement and differential subsidence (as shown in the image below), this methodology is used to quantify the induced stresses from the trenching operations.



Pipeline, considered as a beam

These stresses are calculated assuming a bed of rock is present directly below the pipe, either side of the road crossing. The maximum theoretical embedment is calculated from pipe laying oprations, taking into account the self weight of the pipe and the weight of the compacted backfill. This embedment then combined with the predicted service embedment from the proposed surcharge loadings calculated in §5.2 above. This figure of embedment is then used to calculate the resultant bending moment created, and so estimate a conservative figure for the induced stress caused during pipelaying operations.

§6.1.1 Estimated pipeline embedment during pipelaying - [3] § C.4.4

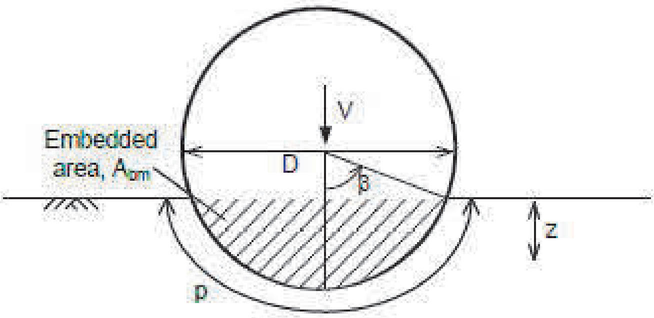


Figure 1 - Pipe embedded cross section.

Estimated pipe embeddment during laying (iteritative approach) $z := 1\ mm$

Cord half angle $\beta(z) := \operatorname{acos}\left(1 - \frac{2\,z}{OD_{tot}}\right)$

Surface area of embedded pipe $S_p(z) := \beta(z) \cdot OD_{tot}$ $S_p(z) = 0.02\ m$

Cord length of embedded pipe $C_p := OD_{tot} \cdot \sin(\beta(z))$ $C_p = 0.02\ m$

Soil overburden - [10] §2 $P(z) := \frac{2 \cdot \gamma_{soil} \cdot z}{3}$ $P(z) = 12.67\ Pa$

Ratio shear strength / overburden - [10] §2

$$R_a(z) := \frac{c_u}{P(z)} \qquad R_a(z) = 789.47$$

Adhesion factor - [10] §2

$$A_f(z) := \begin{cases} \text{if } R_a(z) < 1 \\ \quad 0.5 \cdot R_a(z)^{-0.5} \\ 0.5 \cdot R_a(z)^{-0.25} \end{cases} \qquad A_f(z) = 0.09$$

Skin friction resistance - [10] §2

$$U_{sf}(z) := A_f(z) \cdot c_u \cdot S_p(z) \qquad U_{sf}(z) = 0.02\ kN \cdot m^{-1}$$

Overburden resistance - [5] §8.4.2

$$Q_{ps}(z) := N_c \cdot c_u \cdot C_p \qquad Q_{ps}(z) = 1.1\ kN \cdot m^{-1}$$

Total soil resistance

$$F_p(z) := U_{sf}(z) + Q_{ps}(z) \qquad F_p(z) = 1.12\ kN \cdot m^{-1}$$

Total surcharge

$$Q_{tot} = 7.49\ kN \cdot m^{-1}$$

Embedment check

$$Check_{Embedment} := \begin{cases} \text{if abs}\left(\frac{Q_{tot}}{F_p(z)}\right) < 1 \\ \quad \text{return “Embedment OK”} \\ \text{return “Amend embedment”} \end{cases} = \text{“Embedment OK”}$$

§6.1.2 Induced pipe stresses from trenching operations

Theoretical beam length - [4] §8 Table 8.1 (ref. 2b)

$$L_z := \left(\frac{3 \cdot z \cdot E \cdot I_{y\_max}}{Q_{tot}}\right)^{0.25} \qquad L_z = 0.71\ m$$

Theoretical beam length

$$L_z := \min(L_z, w) \qquad L_z = 0.71\ m$$

Resultant moment - [4] §8

$$M_B := Q_{tot} \cdot L_z^{\ 2} \qquad M_B = 3.79\ kN \cdot m$$

Induced stress - [4] §8

$$\sigma_{fx} := \frac{M_B \cdot z}{I_{y\_max}} \qquad \sigma_{fx} = 1.25\ MPa$$

The induced stress is combined with the membrane and bending stresses calculated in §6.5 below:

§6.2 Circumfrential stresses due to vertical load - [3] § D.3

§6.2.1 Vertical ultimate bearing capacity- [3] § C.4.4.2

Depth of grade level to pipe axis $Z_h := H_{max} + OD_{tot} - z$ $Z_h = 1.71\ m$

Effective overburden density $\gamma' := \dfrac{H_{soil} \cdot \gamma_{soil} + H_{road} \cdot \gamma_{road}}{H_{max}}$ $\gamma' = 1802.32\ kg \cdot m^{-3} \cdot g$

Bearing capacity factors - [3] § C.4.4.2 (a)

$$N_q := \exp(\pi \cdot \tan(\phi)) \cdot \tan\left(\tan\left(45\ deg \cdot \frac{\phi}{2}\right)\right)$$

$N_q = 1.71$

$$d_q := 1 + 2 \cdot \tan(\phi) \cdot (1 - \sin(\phi))^2 \cdot \operatorname{atan}\left(\frac{Z_h}{C_p}\right)$$

$d_q = 1.43$

$N_y := 1.5 \cdot (N_q - 1) \cdot \tan(\phi)$ $N_y = 0.67$

$BL := 0.1$ $BL = 0.1$

$S_y := 1 - BL$ $S_y = 0.9$

$d_y := 1$ $d_y = 1$

$S_q := 1 + \sin(\phi) \cdot BL$ $S_q = 1.05$

$q_n := H_{max} \cdot \gamma_{soil}$ $q_n = 30.4\ kPa$

$\gamma' = 17.67\ kN \cdot m^{-3}$

$C_p = 0.02\ m$

Vertical ultimate pipe bearing capacity - [3] C.4.4.2 (a)

Drained condition, non-cohessive soil (i.e. SAND)

$$P_{we} := 0.95 \cdot ((0.5 \cdot \gamma' \cdot C_p \cdot N_y \cdot S_y \cdot d_y) + (S_q \cdot N_q \cdot d_q \cdot (q_n + c' \cdot \cot(\phi))) - (c' \cdot \cot(\phi)))$$

$P_{we} = 4729.05\ kPa$

§6.2.2 Circumfrential Ring Interaction - [3] § D.3.1

Load angle - [3] § C.4.1.3(a) $\alpha_{pipe} := 180\ deg$

Support angle - [3] § C.4.1.3

$$\beta_{pipe} := 2 \cdot asin\left(\frac{Q_{ps}(z)}{P_{we} \cdot OD_{tot}}\right)$$

$\beta_{pipe} := max(\beta_{pipe}, 70)\ deg$ $\beta_{pipe} = 70\ deg$

Moment coefficients and deflection factors for directly transferred vertical load - [3] Table D.1

Selected support angle from table	$\beta_{pipe'} := 70\ deg$
Moment coefficient, base	$K_b := 0.178$
Moment coefficient, top	$K_t := 0.141$
Moment coefficient, side	$K_s := -0.145$
Deflection factor, vertical	$k_y := 0.102$

Moment, base - [3] § D.3	$M_b := K_b \cdot q_{tot} \cdot R_g$	$M_b = 72.16\ N \cdot mm$
Moment, top - [3] § D.3	$M_t := K_t \cdot q_{tot} \cdot R_g$	$M_t = 57.16\ N \cdot mm$
Moment, side - [3] § D.3	$M_s := K_s \cdot q_{tot} \cdot R_g$	$M_s = -58.79\ N \cdot mm$

§6.3 Pipeline hoop stress analysis

Allowable hoop stress (Steel Pipes) - [2] § 8.1.1 / Table 1 $\sigma'_{hoop} := 0.72 \cdot \varepsilon_{smys}$ $\sigma'_{hoop} = 208.8\ MPa$

§6.3.1 Circumferential stress - depressurised or pressurised pipes

Hoop stress from internal gas pressure - [3] Boiler formula §D.1.1 $\sigma_{in} := \dfrac{\rho \cdot D_g}{2 \cdot th_{min}}$ $\sigma_{in} = 19.87\ MPa$

Hoop compression from permanent overburden $\sigma_v := \dfrac{-Q_{nr}}{2 \cdot th_{min}}$ $\sigma_v = -0.32\ MPa$

Hoop stress (depressurised) $\sigma_h := \sigma_v$ $\sigma_h = -0.32\ MPa$

Hoop stress (pressurised) $\sigma_{h'} := \sigma_v + \sigma_{in}$ $\sigma_{h'} = 19.55\ MPa$

Hoop stress utilisation $UTL_{hoop} := \dfrac{\max\left(\text{abs}\left(\sigma_{h'}\right), \text{abs}\left(\sigma_{in}\right)\right)}{\sigma'_{hoop}}$ $UTL_{hoop} = 0.1$

§6.3.1 Additional stress in bends - [3] D.1.2

Stress, inside of bend $\sigma_{p\_bi} := \sigma_{h'} \cdot \dfrac{2 \cdot R_{bend} - 0.5 \cdot OD_{max}}{2 \cdot R_{bend} \quad OD_{max}}$ $\sigma_{p\_bi} = 21.53\ MPa$

Stress, outside of bend $\sigma_{p\_bu} := \sigma_{h'} \cdot \dfrac{2 \cdot R_{bend} + 0.5 \cdot OD_{max}}{2 \cdot R_{bend} + OD_{max}}$ $\sigma_{p\_bu} = 18.14\ MPa$

Maximum stresss $\sigma_p := \max\left(\sigma_{p\_bi}, \sigma_{p\_bu}\right)$ $\sigma_p = 21.53\ MPa$

Resultant stresss

```
σh' := || if R_bend ≥ 10 · OD_pipe
       ||   || return σh'
       || return σp
```

$\sigma_{h'} = 21.53\ MPa$

Hoop stress utilisation $UTL_{hoop} := \dfrac{\sigma_{h'}}{\sigma'_{hoop}}$ $UTL_{hoop} = 0.1$

§6.2.3 Pipe ovality (steel pipes)

Allowable pipe ovalization - [2] § 8.2 $\Delta_{D\_allow} := 5\%$

Allowable pipe deflection - [2] § 8.2 $\delta'_y := \Delta_{D\_allow} \cdot OD_{pipe}$ $\delta'_y = 5.72\ mm$

Factory out-of-roundness tolerances - [20] PD-8010-2 (2004) §G.1.2 $\delta_{tol'} := \max\left(OD_{max} - OD_{min}, \delta_{tol}\right)$ $\delta_{tol'} = 2.29\ mm$

Deflection of ring cross section (max) - i.e. no trench support [3] §D.4.1 $\delta_y := \dfrac{k_y \cdot Q_{tot} \cdot R_g^{\,3}}{E \cdot I_w}$ $\delta_y = 0.03\ mm$

Soil modulus adjustment factor - [15] §NA.5.2.2 $C_L = 1.29$ $\delta_{tol} = 2.29\ mm$

Overall modulus of soil reaction [15] §NA.5.2.2 $E'' = 7000\ kPa$

Re-rounding of Pressure Pipes [15] §NA.6.2.5

$$\Delta D_R := \begin{array}{l} \text{if } \rho < 3\ bar \\ \quad \text{return } 1 \\ \text{return } 1 - \left(\dfrac{\rho}{40\ bar}\right) \end{array}$$

$\Delta D_R = 0.53$

Ovalisation Unpressurised Pipes - [15] §NA.6.2.5

$$\Delta D := \frac{K_x \cdot \left(\left(D_L \cdot P_e\right) + P_s\right)}{\left(\dfrac{8 \cdot E_s \cdot I_w}{OD_{pipe}^{\,3}}\right) + 0.061 \cdot E''}$$

Ovalisation - Unpressurised Condition (%) $\Delta D = 0.03\%$

Ovalisation - Unpressurised Condition (mm) $\delta_{y'} := \Delta D \cdot OD_{pipe}$ $\delta_{y'} = 0.04\ mm$

Total pipe ovalization - Unpressurised Condition (%) $\delta_{tot} := \min\left(\delta_y, \delta_{y'}\right) + \delta_{tol'}$ $\delta_{tot} = 2.32\ mm$

Pipe ovalization utilisation - Unpressurised Condition (%) $UTL_{defl} := \dfrac{\delta_{tot}}{\delta'_y}$ $UTL_{defl} = 0.41$

§6.5.1 Elastic buckling limits - With soil support

Critical long term buckling pressure - [15] §NA.6.2.3 Eq (21a)

$$P_{crl} := 0.6 \cdot \left(\frac{E \cdot I_w}{D_g^{\ 3}}\right)^{0.33} \cdot E''^{0.67} \qquad P_{crl} = 3162.62\ \frac{kN}{m^2}$$

Critical short term buckling pressure - [15] §NA.6.2.3 Eq (21a)

$$P_{crs} := 0.6 \cdot \left(\frac{E_s \cdot I_w}{D_g^{\ 3}}\right)^{0.33} \cdot E''^{0.67} \qquad P_{crs} = 3162.62\ \frac{kN}{m^2}$$

Factor of safety againgst buckling - [15] §NA.6.2.3 Eq (21)

$$F_s := \frac{1}{\left(\frac{P_e}{P_{crl}}\right) + \left(\frac{P_s}{P_{crs}}\right)} \qquad F_s = 48.24$$

§6.5.1 Allowable Factor of safety againgst buckling (Plastic pipes or steel pipes below 7 bar)

Minimum buckling FoS - [2] §7.3 $\quad F_{buc} := 3.0$

Primary Buckling Check (with soil support)

$$Check := \begin{array}{l} \text{if } F_s \geq F_{buc} \\ \quad \text{return "PASS"} \\ \text{return "FAIL"} \end{array} \qquad Check = \text{"PASS"}$$

Pipe buckling utilisation

$$UTL_{pe} := \frac{1}{F_s} \qquad UTL_{pe} = 0.02$$

§6.5.2 Elastic buckling limits - Without soil support

Critical long term buckling pressure - [15] §NA.6.2.3 Eq (21a)

$$P_{cra} := \frac{24 \cdot E_s \cdot I_w}{D_g^{\ 3}} \qquad P_{cra} = 71116.24\ \frac{kN}{m^2}$$

Factor of safety againgst buckling - [15] §NA.6.2.3 Eq (22)

$$F_{s'} := \frac{P_{cra}}{P_e + P_s} \qquad F_{s'} = 1084.76$$

Depth of cover check - [15] §NA.6.2.3 Eq (22)

$$F_{s'} := \begin{array}{l} \text{if } H_{min} \geq 1.5\ m \\ \quad \text{return } F_s \\ \text{return } F_{s'} \end{array} \qquad F_{s'} = 48.24$$

Secondary Buckling Check (without soil support)

$$Check := \begin{array}{l} \text{if } F_{s'} \geq F_{buc} \\ \quad \text{return "PASS"} \\ \text{return "FAIL"} \end{array} \qquad Check = \text{"PASS"}$$

Pipe buckling utilisation

$$UTL_{pe'} := \frac{1}{F_{s'}} \qquad UTL_{pe'} = 0.02$$

Note, as it can be seen the pipe is capable of adaquately supporting the surcharge loading without soil support for a temporary / short term loading case. However precautions should always be taken onsite during construction if adjacent excavations are required which could tempoararily undermine the surrounding soil support.

§7 Pipeline structural analysis

§7.1 Maximum allowable stresses

Allowable hoop stress - [2] § 8.1.1 / Table 1 $\sigma'_{hoop} = 208.8\ MPa$

Allowable equivalent stress (membrane componets) - [2] § 8.1.2 $\sigma'_{mem} := 0.8 \cdot \varepsilon_{smys}$ $\sigma'_{mem} = 232\ MPa$

Allowable equivalent stress (stress componets) - [2] § 8.1.2 $\sigma'_{stress} := 0.9 \cdot \varepsilon_{smys}$ $\sigma'_{stress} = 261\ MPa$

§7.2 Axial stress - restrained or unrestrained pipes

Axial stress unrestrained pipes - [3] §D.1.3.1

$$\sigma_{ax} := \frac{\rho \cdot (OD_{max} - 2 \cdot th_{min})^2}{OD_{max}^2 - ((OD_{max} - 2 \cdot th_{min})^2)} \qquad \sigma_{ax} = 9.01\ MPa$$

Axial stress restrained pipes [3] §D.1.3.1 $\sigma_{ax'} := \nu \cdot \sigma_{h'}$ $\sigma_{ax'} = 6.46\ MPa$

§7.3 Axial stress due to temperature fluctuations - depressurised or pressurised pipes

Temperature differential (depressurised) $\Delta T := \max(T_4 - T_2, T_1 - T_3)$ $\Delta T = 10\ \Delta°C$

Temperature differential (pressurised) $\Delta T' := \max(T_2 - T_5, T_6 - T_1)$ $\Delta T' = 25\ \Delta°C$

Axial stress - [3] § D.2.2 $\sigma_{at} := \alpha_g \cdot E \cdot \Delta T$ $\sigma_{at} = 24.57\ MPa$

Axial stress - [3] § D.2.2 $\sigma_{at'} := \alpha_g \cdot E \cdot \Delta T'$ $\sigma_{at'} = 61.43\ MPa$

Tensile stress utilisation

$$UTL_{ten} := \frac{\max(\sigma_{at'}, \sigma_{at})}{\sigma'_{stress}} \qquad UTL_{ten} = 0.24$$

§7.4 Bending stresses - depressurised pipe

Bending stress in pipe wall - [3] § D.3.1

$$\sigma_{qb} := \mathrm{abs}\left(\frac{M_b}{W_w}\right) \qquad \sigma_{qb} = 11.65\ MPa$$

$$\sigma_{qt} := \mathrm{abs}\left(\frac{M_t}{W_w}\right) \qquad \sigma_{qt} = 9.23\ MPa$$

$$\sigma_{qs} := \mathrm{abs}\left(\frac{M_s}{W_w}\right) \qquad \sigma_{qs} = 9.49\ MPa$$

Max bending stress in pipe wall $\sigma_q := \max(\sigma_{qb}, \sigma_{qt}, \sigma_{qs}) + \sigma_{fx}$ $\sigma_q = 12.9\ MPa$

Pipe utilisation - bending

$$UTL_q := \frac{\sigma_q}{\sigma'_{stress}} \qquad UTL_q = 0.05$$

§7.5 Bending stesses - pressurised pipe

Rerounding factor - [3] § D.3.1

$$f_{rr} := \frac{1}{1 + \frac{2 \cdot \rho \cdot {R_g}^3 \cdot k_y}{E \cdot I_w}}$$

$f_{rr} = 0.98$

Bending stress in pipe wall (pressurised) - [3] § D.3.1

$$\sigma_{qb'} := \mathrm{abs}\left(\frac{f_{rr} \cdot M_b}{W_w}\right)$$

$\sigma_{qb'} = 11.48\ \mathbf{\mathit{MPa}}$

$$\sigma_{qt'} := \mathrm{abs}\left(\frac{f_{rr} \cdot M_t}{W_w}\right)$$

$\sigma_{qt'} = 9.09\ \mathbf{\mathit{MPa}}$

$$\sigma_{qs'} := \mathrm{abs}\left(\frac{f_{rr} \cdot M_s}{W_w}\right)$$

$\sigma_{qs'} = 9.35\ \mathbf{\mathit{MPa}}$

Max bending stress in pipe wall (pressurised)

$$\sigma_{q'} := \max\left(\sigma_{qb'}, \sigma_{qt'}, \sigma_{qs'}\right) + \sigma_{fx}$$

$\sigma_{q'} = 12.72\ \mathbf{\mathit{MPa}}$

Pipe utilisation - bending

$$UTL_{q'} := \frac{\sigma_{q'}}{\sigma'_{stress}}$$

$UTL_{q'} = 0.05$

§7.6 Depressurised & operational including occasional load cases - [2] § 8.1.2

The maximum equivalent stress is calculated for three load cases with the inputs summarised below:

Hoop stress (depressurised)	$\sigma_h = -0.32\ MPa$
Hoop stress (pressurised)	$\sigma_{h'} = 21.53\ MPa$
Bending stress (depressurised)	$\sigma_q = 12.9\ MPa$
Bending stress (pressurised)	$\sigma_{q'} = 12.72\ MPa$
Axial stress (unrestrained)	$\sigma_{ax} = 9.01\ MPa$
Axial stress (restrained)	$\sigma_{ax'} = 6.46\ MPa$
Axial stress (depressurised)	$\sigma_{at} = 24.57\ MPa$
Axial stress (pressurised)	$\sigma_{at'} = 61.43\ MPa$

Case 1 - Depressurised & unrestrained pipe - [2] § 8.1.2

Hoop stress	$\sigma_h := \sigma_h$	$\sigma_h = -0.32\ MPa$
Circumferential stress (max)	$\sigma_c := \sigma_q + \sigma_h$	$\sigma_c = 12.58\ MPa$
Circumferential stress (min)	$\sigma_{c'} := -\sigma_q + \sigma_h$	$\sigma_{c'} = -13.22\ MPa$
Longitudinal axial stresses (max)	$\sigma_{a1} := \sigma_{at}$	$\sigma_{a1} = 24.57\ MPa$
Longitudinal axial stresses (min)	$\sigma_{a1'} := -\sigma_{at}$	$\sigma_{a1'} = -24.57\ MPa$

Von Mises equivalent stress

Membrane stresses components	$\sigma_{e1'} := \sqrt{\sigma_h^2 + \sigma_{a1}^2 - \sigma_h \cdot \sigma_{a1}}$	$\sigma_{e1'} = 24.73\ MPa$
	$\sigma_{e2'} := \sqrt{\sigma_h^2 + \sigma_{a1'}^2 - \sigma_h \cdot \sigma_{a1'}}$	$\sigma_{e2'} = 24.41\ MPa$
	$\sigma_{e'} := \max(\sigma_{e1'}, \sigma_{e2'})$	$\sigma_{e'} = 24.73\ MPa$
Membrane stress utilisation	$UTL_{m1} := \frac{\sigma_{e'}}{\sigma'_{mem}}$	$UTL_{m1} = 0.11$
Membrane & bending stresses	$\sigma_{e3'} := \sqrt{\sigma_c^2 + \sigma_{a1}^2 - (\sigma_c \cdot \sigma_{a1})}$	$\sigma_{e3'} = 21.28\ MPa$
	$\sigma_{e4'} := \sqrt{\sigma_c^2 + \sigma_{a1'}^2 - (\sigma_c \cdot \sigma_{a1'})}$	$\sigma_{e4'} = 32.73\ MPa$
	$\sigma_{e5'} := \sqrt{\sigma_{c'}^2 + \sigma_{a1}^2 - (\sigma_{c'} \cdot \sigma_{a1})}$	$\sigma_{e5'} = 33.22\ MPa$
	$\sigma_{e6'} := \sqrt{\sigma_{c'}^2 + \sigma_{a1'}^2 - (\sigma_{c'} \cdot \sigma_{a1'})}$	$\sigma_{e6'} = 21.3\ MPa$
	$\sigma_{eq'} := \max(\sigma_{e3'}, \sigma_{e4'}, \sigma_{e5'}, \sigma_{e6'})$	$\sigma_{eq'} = 33.22\ MPa$
Membrane & bending stress utilisation	$UTL_{s1} := \frac{\sigma_{eq'}}{\sigma'_{stress}}$	$UTL_{s1} = 0.13$