Structural design of buried thermoplastic piping systems

September 2023

Contents

1. Introduction

The purpose of structural design is to ensure that a buried pipeline will be stable when subjected to loads for its intended design lifetime but without over specification.

Flexible pipe materials deflect towards an oval shape in response to vertical loads (from weight of the soil, static loads such as structures, and dynamic loads e.g. traffic) and can benefit from significant support from their surrounding embedment.

This BPF Pipes Group document provides pipeline designers with additional information when undertaking the structural design of thermoplastic piping systems using the Marston-Spangler method in BS 9295: 2020.

The information is applicable to buried thermoplastic piping systems for pressure and non-pressure applications.

It is important to note that:

- For drains and sewers constructed to Approved Document H of the Building Regulations or to NHBC Standards, pipes with depth of cover less than 0.6 m (fields and gardens) or 0.9 m (roads) typically require additional protection such as a concrete slab from vertical loads. **In these cases, pipe structural design calculations are not carried out.**
- For large diameter plastic pipes for non-pressure applications, the use of an alternative, suitability validated, design method to the Marston-Spangler method in BS 9295 might be more appropriate to avoid overly conservative design. **The BPF Pipes Group recommend that pipeline designers seek advice directly from the pipe manufacturer for pipes greater than 900 mm.**
- The information in this document is for piping systems manufactured from thermoplastic materials only and does not apply to, and should not be used for, glass reinforced plastics, thin-walled steel or steel reinforced plastics. Whilst these pipes may be categorised as 'flexible', they have their own material-specific design requirements.
- A list of specifications for thermoplastic piping systems for non-pressure wastewater and highways applications, and for pressure water supply, gas, and wastewater applications is available from: https://www.bpfpipesgroup.com/technical-information/specification-guidance/
- In the case of dispute, BS 9295: 2020 takes precedence over this document.

2. Background and reference sources

2.1 Background

The method used to determine the structural design of a buried flexible pipeline was first proposed by Dr Anson Marston of Iowa State University during the early 20th Century and further developed by Merlin Spangler in the 1940s for predicting pipe ring deflection. Information on the history and development of the Marston-Spangler method and its principals are given in Golubev, (2021)[1].

This was further developed into a method for structural design of underground non-pressure uPVC pipelines by Work (1986)[2].

In the 1980s and 1990s, design calculations using the WRc method[2] were validated by site measurements for structured wall plastic pipes up to 300mm diameter over a period of 2-3 years. Deflection was measured at the time of installation up to the point of water company adoption, generally around two years. The work confirmed that measured values were very conservative compared to calculations and that, as anticipated, a structural equilibrium between the pipe and the soil structure is typically reached after two years. Beyond this, further deflection is minimal.

Since that time, field experience has been gained with this method as plastic piping systems over a wider range of diameters have been designed and installed.

It is acknowledged that the use of the Marston-Spangler method for plastic pipes leads to a conservative design solution[1,3]. Whilst for flexible steel pipe (for which the Marston-Spangler method was first developed), the short- and long-term properties of the pipe are the same, this is not true for plastic pipes. When subjected to external loads such as weight of soil cover and traffic, pipes manufactured from visco-elastic materials such as polyethylene, polypropylene, or poly(vinylchloride) will tend to deform (creep) under constant (sustained) loading conditions until the structural equilibrium between the pipe and the soil structure is reached. These time-dependent properties are not appropriately considered in the Marston-Spangler method. This generally results in the selection of higher stiffness pipe or tighter specification of bedding and backfill than is required to satisfy deflection limits and factors of safety against buckling set by the pipeline designer.

Dr Jonathan Olliff developed guidance on the use of the Marston-Spangler method for the structural design of buried plastic pipes which considered the effect of creep under applied loads. This was included in WRc's Pipe Materials Selection Manual for Water

Supply (1988, 1995)[4, 5] and FWR's Materials Selection Manual for Sewers, Pumping Mains and Manholes (1993)[6].

Dr Olliff's work in the PMSM (1995)[5] was recognised as the UK "established method" and was taken into the National Annex A of BS EN 1295-1: 1997[8] and more recently into BS 9295: 2020[7] which replaced the National Annex.

Research into additional design methods for large diameter structured wall plastic pipes is ongoing.

2.2 References

1. Comparative analysis of UK structural design methodologies for large diameter thermoplastic pipes under buried conditions. Golubev, 2021.

2. ER201E. Guide to the water industry for the structural design of underground non-pressure uPVC pipelines. 1986.

3. CIRIA Report 78. Design and construction of buried thin-wall pipes. CIRIA, 1978.

4. Pipe Materials Selection Manual for Water Supply. WRc, 1988.

5. Pipe Materials Selection Manual for Water Supply. WRc, 1995.

6. Materials Selection Manual for Sewers, Pumping Mains and Manholes. FWR, 1993.

7. BS 9295: 2020 Guide to the structural design of buried pipes. BSI, 2020.

8. BS EN 1295-1: 1997 Structural design of buried pipelines under various conditions of loading. Part 1: General requirements. National Annex A (informative): Calculation procedure for UK established method.

9. BS EN 1295-1: 2019 Structural design of buried pipelines under various conditions of loading. General requirements. BSI, 2019.

10. BS EN 12201-2: 2011+A1:2013. Plastics piping systems for water supply, and for drainage and sewerage under pressure. Polyethylene (PE). Pipes. BSI, 2013.

11. BS EN 805: 2000 Water supply - Requirements for systems and components outside buildings. BSI, 2000.

12. Design Manual for Roads and Bridges. CD533 Drainage design: Determination of pipe and bedding combinations for drainage works. National Highways, Dec 2021.

3. Terms and symbols used in structural design of thermoplastic piping systems

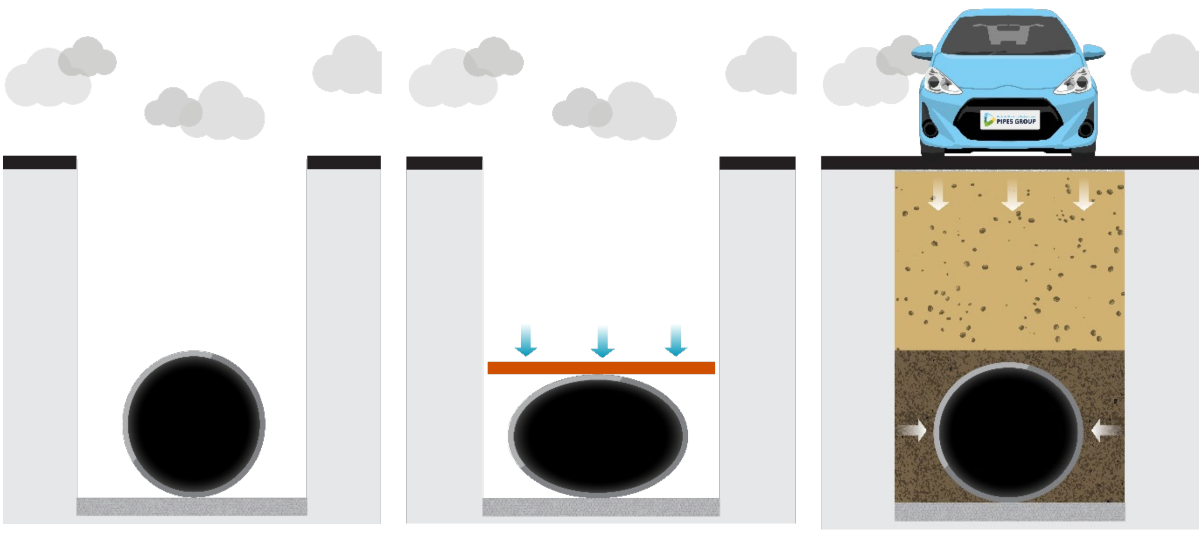
3.1 Terms

Materials / Pipe

Flexible pipes: The UK design practice classifies pipes based on potential failure modes under external load. A flexible pipe is described as one whose properties are such that the first limit state reached is either excessive deformation or buckling of the pipe wall. All thermoplastic pipes are classified as flexible.

In practice, this means that, when subjected to a vertical load, a flexible pipe will deform until it is constrained by the surrounding embedment. Where that passive side support is not sufficient (for example due to poor embedment compaction), the pipe fails by excessive deformation or buckling of the pipe wall. As such, the type and compaction of the embedment is important to the overall structural performance of a flexible pipe (see figure 1).

Figure 1 Schematic to show behaviour of flexible pipe under load



(a) Circular pipe in open trench

(b) Unconstrained deformation under a vertical load (without side support)

(c) Constrained deformation under a vertical load (with side support)

Ovality or out-of-roundness: The difference between the maximum external diameter and the minimum external diameter in the same cross-section of the pipe or spigot.

Ovality comes about from manufacturing tolerances and storage (stacking, coiling) prior to installation. Maximum ovality is defined by the product standard.

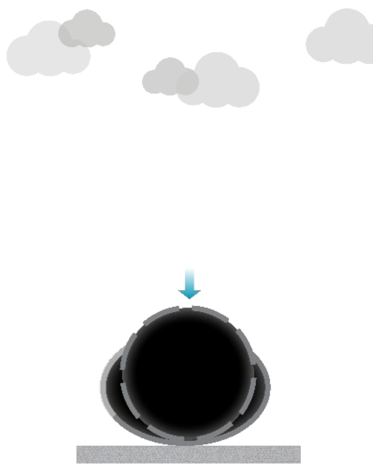
Note: Ovality is not used in structural design calculations and should not be confused with pipe ring deflection.

Pipe ring deflection: The deformation of a flexible pipe when subjected to externally applied vertical loads.

Loads on the pipe (soil cover, traffic) cause the pipe to reduce in its vertical diameter and increase its horizontal diameter (see figure 2).

In buried pipelines, this deformation is resisted by the ring stiffness of the pipe, together with the stiffness of the native soil and the presence and degree of compaction of sidefill in the trench. The pipe deforms until an equilibrium is reached between the vertical soil pressure and the horizontal passive resistance.

Figure 2 Schematic to show deformation of an unconstrained flexible pipe under applied load



Ring deflection is given by the change of vertical pipe diameter divided by the nominal diameter of the pipe and is typically expressed as a percentage of the nominal diameter of the pipe.

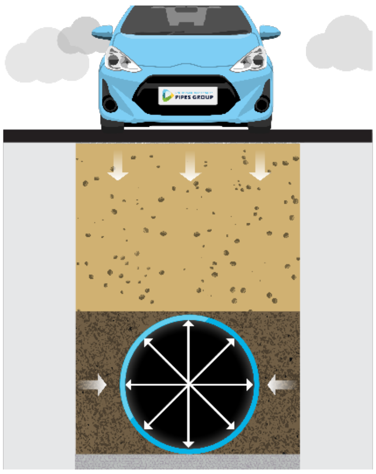
Note: BS 9295: 2020[7] uses the term "ovalization" in place of ring deflection.

Rerounding: The change in shape of a deformed pipe due to hydrostatic pressure acting on the internal surface of the pipe and against the effect of externally applied loads.

For non-pressure buried pipes, the calculation of long-term deflection only takes account of the reduction in the stress from externally applied vertical loads in the pipe wall due to creep (see "Behaviour of visco-elastic materials" below).

In a pressurised plastic pipe, the stress in the pipe wall due to the internal hydrostatic pressure will cause radial expansion over time, reaching equilibrium when the pipe diameter is constrained by the surrounding fill material (see figure 3).

Figure 3 Schematic to show rerounding of buried pipe under internal pressure



For buried pressure pipes, the calculation of long-term deflection should therefore take account of both the reduction in the stress due to creep and the radial expansion over time. The deformation caused by the vertical loads is reduced as internal pressure increases. Rerounding cannot entirely reduce deformation from vertical loads and the pipe should never be pressurised above its pressure rating in attempt to do so[15].

BS EN 1295-1: 2019[9] advises that the extent to which the rerounding process reduces pipe deformation after pressurisation in a buried pipe depends on factors such as pipe properties, ratio of the internal pressure to the external pressure, and the amount of consolidation of the soil which has taken place around the pipe.

In BS 9295: 2020 7.2.8[7] (also BS EN 1295-1: 1997 NA.6.2.5[8]), the effect of rerounding (radial expansion over time) is applied to initial deflection but omitted from calculation of long-term deflection. An amendment to BS 9295: 2020 is being prepared to address this. The rerounding factor is shown in this document in the calculation of long-term deflection of a pressurised plastic pipe.

Pressure rating: The ability of a pipe to resist internal water pressure acting on it in the radial direction.

Nominal pressure rating (PN): A numerical designation used for reference purposes related to the mechanical characteristics of the component of a piping system. For plastic piping systems conveying water, it corresponds to the allowable operating pressure (PFA) in bar, which can be sustained with water at 20 °C with a design basis of 50 years.

Modulus of elasticity of a pipe material in ring bending (E): The relationship between stress (σ) and strain (ε) is described by Hooke's Law, such that $\sigma / \varepsilon = E$ (elastic modulus of the material).

Behaviour of visco-elastic materials: For visco-elastic materials such as polyethylene, polypropylene and PVC, the relationship between stress and strain is non-linear over time. The elastic modulus (modulus of elasticity) of a visco-elastic material, or the response of a visco-elastic material to a constant stress or constant strain are considered to change over time. For pipes of visco-elastic material, the short-term modulus of elasticity of a pipe material in ring bending E_S and long-term modulus E_L used for structural design are not the same.

Ring stiffness: The ability of a pipe to resist forces acting on it in the radial direction.

Nominal pipe ring stiffness (SN): Numerical designation of the ring stiffness of a pipe or fitting, which is a convenient round number indicating the minimum required ring stiffness of the pipe or fitting. For example, SN2 refers to ring stiffness of 2 kN/m^2. Nominal pipe ring stiffness is measured at 20 °C.

- Nominal pipe ring stiffnesses SN2, SN4 or SN8 are typically used in the UK for non-pressure applications.
- Nominal pipe ring stiffness is not typically quoted for pressure pipes.
- Short-term ring stiffness (S_i) - For the purposes of design, short-term pipe stiffness is taken to be SN.
- Long-term ring stiffness (S_L) – Due to the visco-elastic behaviour of plastic pipes, the long-term pipe ring stiffness is less than the initial or short-term value. It is typically determined by the short-term pipe stiffness divided by the creep ratio. For PVC-U pipes, creep ratio is ≤ 2.5 and for PE / PP pipes, creep ratio is ≤ 4.

Embedment

Deflection Lag Factor (D_L): The Deflection Lag Factor is used in the design equations to give an indication of the degree of settlement or consolidation which occurs in the sidefill around the pipe over time. A greater level of initial compaction would mean less change over time and therefore a lower value of Deflection Lag Factor.

- If sidefill is sufficiently well compacted, it is possible that the Deflection Lag Factor could be taken as unity and no further pipe deformation would occur due to soil settlement over time.
- If the pipe is to be pressurised to at least 3 bar within one year of backfilling and laid at a depth of no greater than 2.5 m, any deformation from soil settlement to that date would be opposed by internal pressure. The Deflection Lag Factor used in the design can be taken as unity. [Source: BS 9295: 2020 7.2.4]

Proctor Density or Compacted Density: A factor to describe the compaction of bedding.

It is a measure of compaction achieved on site compared to that which can be achieved for the bedding material in a laboratory using the Proctor Test.

- In UK design, the Modified Proctor Density is used. In the Modified Proctor Test, the soil is compacted in a mould in five layers with a rammer of 4.5 kg with a fall of 45 cm.
- In practice, the level of compaction is not often directly measured on site. A method of work is typically used, whereby the type of fill material and quality of workmanship is assumed to achieve a minimum value for Modified Proctor Density or Compacted Density.
- *Note: The Standard Proctor Density is not commonly used in UK design but is similar to Modified Proctor Density, except it uses a different mass rammer and fall distance.*

Modulus of soil reaction (E'): Empirical value used to determine the magnitude of the support provided by the native soil or the embedment. Easily deformable (weaker) soils have a lower value of E'.

- The overall or combined modulus of soil reaction is the composite effect of native soil and embedment. The relative importance of each component depends on the trench width.
- Where the trench width is more than 4.3 times the pipe external diameter, only the modulus of the embedment is considered [Source: BS 9295:2020, 7.2.5].

- *Note: E' cannot be directly measured on site. Further information is given in Sections 5 and 6.*

3.2 Symbols

The parameters used in the equations, their symbols, and the units in which each is used in the equations are listed in Annex B. For each parameter, the suggested source of data is given.

4. Process for structural design of plastic pipes

4.1 Overview

The structural design of a pipeline consists of assessing the structural loadings which the pipeline should be designed to withstand and selecting appropriate pipe and embedment strengths. These, in combination, should provide an appropriate factor of safety against failure under the expected design loadings.

A flow chart detailing the design process is shown in Figure 4.

It is recommended that the data required for structural design are identified before the Site Investigation is undertaken. This might include, but not be limited to, properties of native soil, depth of water table, location of adjacent structures (temporary during construction or permanent) and geographical features (for example steep slopes, embankments etc.).

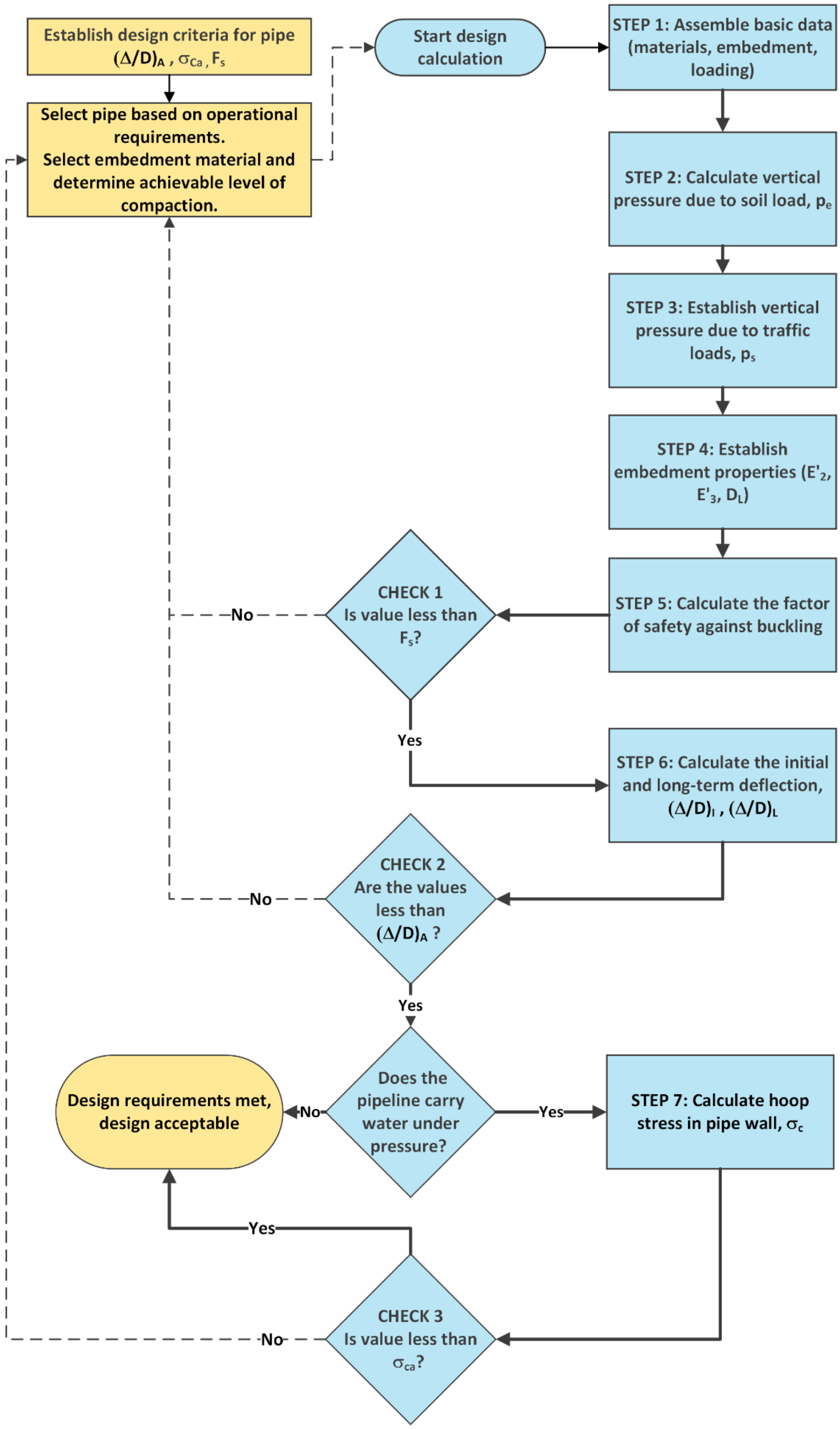
BS 9295: 2020 7.2 gives the formulae for the Marston-Spangler design procedure for flexible pipes (GRP, steel and thermoplastics) for pressure and non-pressure applications. This BPF Pipes Group document presents these formulae separately for thermoplastic pressure pipelines (Section 5) and thermoplastic non-pressure pipelines (Section 6).

The Marston-Spangler method for the structural design of buried plastic pipes does not differentiate between pressure and non-pressure pipelines. However, modification to the method enables the effects of rerounding after pressurisation to be accommodated. This is shown in Section 5, Step 6.

For more complex design and installation cases, modifications may be required to the method. Guidance can be sought from the pipe manufacturer.

Best practice on installation of pipes including bedding and backfill is given in BS EN 1610 "*Construction and testing of drains and sewers*". The pipe manufacturer can also advise on recommended bedding material.

Figure 4 Design process



4.2 Design criteria

The designer, giving due consideration to the requirements to the pipeline owner or any approving organisation(s), sets the following criteria against which the design calculations are checked:

- Minimum factor of safety against buckling, F_s.
- Maximum allowable deflection limit for the pipe, $(\frac{\Delta}{D})_A$.
- Maximum allowable stress limit for the pipe material, σ_{ca} (pressure pipes only).

An explanation for each is given below.

Minimum factor of safety against buckling, F_s: Compressive forces in the pipe wall due to external pressures (and/or internal vacuum) can cause failure due to buckling. For pipes installed in well compacted backfill, the embedment increases the ability of the pipe to resist buckling. BS 9295: 2020 7.2.7[7] recommends that a value of F_s not less than 2.0 is used where soil support is taken into account and not less than 1.5 where soil support is discounted. Soil support might be discounted where, for example, a pipeline has a shallow burial depth and could lose its side support if trenches for other utilities are dug nearby. National Highways Design Manual for Roads and Bridges[12] specifies that a value of F_s of 2.0 is used.

Maximum allowable deflection limit for the pipe, $(\frac{\Delta}{D})_A$:

- For non-pressure pipes, UK design and construction guidance for adoptable sewers specify a limit of 6%. National Highways Design Manual for Roads and Bridges [12] specifies a limit of 5%.
- For pressure pipes, a limit is not specified. The limit is, in practice, controlled by the ability of the jointing system to remain leaktight under differential deflection in the pipe wall and fitting. The PMSM (1995)[6] suggested a limit of 6%.
- In practice, the deflection limit for a constructed pipeline is mostly dependent on the type of joint and its ability to remain leaktight under a vertical load. Systems with welded joints (typically water supply pipes and sewerage rising mains) can accommodate greater deflections, given in BS EN 805: 2000[11] and BS 9295: 2020[7] as 8%. Guidance can be sought from the pipe / fitting manufacturer.

Maximum allowable stress limit for the pipe material, σ_{ca}: A safety factor is applied to the Minimum Required Strength (MRS) of the pipe to determine the limit.

	MRS (MPa)	Maximum allowable stress limit for the pipe material, σ_{ca} (MPa)
PE80	8.0	6.4
PE100	10.0	8.0
Note: Values are correct at 20 °C, see BS EN 12201-2[10]. For use in Design Check 3 (Section 5, Step 7), σ_{ca} needs to be converted from MPa to kN/m^2 (kPa).		

5. Design calculation – pressure pipes

Step 1: Assemble basic data required for design calculation

The data required for pressure pipe design is given below. The data source, symbols and units are given for each parameter in Annex B. **Where these are used in the calculations, they are shown in bold.** The term is not described each time.

Materials / Pipe

- External diameter of pipe D_o
- Pipe wall thickness t
- Mean diameter D
- Modulus of elasticity of pipe material in ring bending – Short-term E_s
- Modulus of elasticity of pipe material in ring bending – Long-term E_L

Embedment

- Native soil type
- Effective width of trench B_d
- Embedment material type
- Degree of compaction of bedding material

Loading

- Depth of cover H
- Unit weight of soil "overburden" γ
- Type of surface surcharge (main road / field and garden)

Step 2: Calculate vertical pressure due to soil load, p_e

(Also called "overburden pressure")

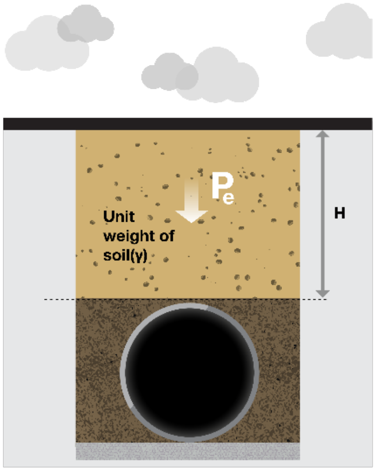
Using Equation 5.1, calculate vertical pressure due to soil load (p_e):

p_e = **Unit weight of soil** x **Depth of cover** = γ.H Eqn (5.1)

[Source: BS 9295: 2020 Equation 27)]

Note: In the absence of specific information being available, 19.6 kN/m² may be assumed for the soil unit weight [Source: BS 9295:2020 7.2.1.]

Figure 5 Schematic to show vertical pressure due to soil load acting on pipe



Step 3: Establish vertical pressure due to traffic loads (surface surcharge), p_s

(Also called "surcharge pressure")

With knowledge of the **Depth of cover (H)** and **Type of surface surcharge**, use Table 1 (Annex A) to establish vertical pressure due to traffic loads, p_s.

Step 4: Establish embedment properties, E'_2, D_L, E'_3

With knowledge of the **Embedment material type**, use the Table 2 (Annex A) to identify the Embedment Class. *Note: The Embedment Class might be specified in the contract.*

For the Embedment Class and the **Degree of compaction of bedding material (M_p)**, use Table 2 (Annex A) to identify the following:

- K_x Deflection coefficient
- E'_2 Modulus of soil reaction, Embedment
- D_L Deflection Lag Factor

For trench width less than 4.3 times the external pipe diameter (i.e. $\mathbf{B_d} < 4.3\ \mathbf{D_o}$) and with knowledge of the **Native soil type**, use Table 3 (Annex A) to establish E'_3 (Modulus of soil reaction for native soil).

Using Equation 5.2, calculate the effective overall modulus of soil reaction (E'):

$E' = E'_2.C_L$ Eqn (5.2)

$$\text{where } C_L = \frac{0.985+0.544\left(\frac{B_d}{D_o}\right)}{\left[\left(1.985-0.456\left(\frac{B_d}{D_o}\right)\right).\left(\frac{E'_2}{E'_3}\right)\right]-\left(1-\left(\frac{B_d}{D_o}\right)\right)}$$

[Source: BS 9295: 2020 Equations 29 and 30]

Note: For trench width greater than 4.3 times the external pipe diameter (i.e. $\boldsymbol{B_d} > 4.3\ \boldsymbol{D_o}$*),* C_L *is unity (has a value of 1), meaning* E'_3 *does not need to be determined and the effective overall modulus of soil reaction E' is taken to be* E'_2*.* (See BS 9295: 2020 7.2.5)

Step 5: Calculate the factor of safety against buckling

Using Equations 5.3 and 5.4, calculate the short and long-term values of p_{cr} using the **Short- term modulus of elasticity of the material (E_s)** and **Long-term modulus of elasticity of the material (E_L)**.

Short-term critical buckling pressure, $p_{crs} = 0.6.\left(\frac{E_S.I}{D^3}\right)^{0.33}.(E')^{0.67}$ Eqn (5.3)

Long-term critical buckling pressure, $p_{crl} = 0.6.\left(\frac{E_L.I}{D^3}\right)^{0.33}.(E')^{0.67}$ Eqn (5.4)

where:

Second Moment of Area of the pipe wall per unit length $I = \mathbf{t}^3/12$

Mean diameter of pipe $D = \mathbf{D_o - t}$

E' is effective overall modulus of soil reaction (see Step 4)

[Source: BS 9295: 2020 Equation 31]

Design Check 1

Using Equation 5.5, check the factor of safety calculated for the proposed pipeline design against the minimum factor of safety against buckling (see 4.2).

Where the cover depth is less than 1.5 m, there is a risk of loss of soil support during work on adjacent utility apparatus. Using Equation 5.6, also check the factor of safety provided by the proposed design against the minimum factor of safety against buckling (see 4.2).

If the calculated factor of safety is lower than the minimum factor of safety against buckling, the pipe selection and embedment materials should be revisited. Repeat steps 4 and 5. If acceptable, move to Step 6.

With soil support, $F_s = \frac{1}{[\left(\frac{p_e}{p_{crl}}\right)+\left(\frac{p_s}{p_{crs}}\right)]}$ Eqn (5.5)

Without soil support, $F_s = \frac{24.(\frac{E_s I}{D^3})}{p_e}$ Eqn (5.6)

where:

p_e is pressure due to soil load “overburden pressure” (see Step 2)

p_s is pressure due to traffic loads “surcharge pressure” (see Step 3)

p_{crs} is short-term critical buckling pressure (see step 5)

p_{crl} is long-term critical buckling pressure (see step 5)

Second moment of area of the pipe wall I = $\mathbf{t}^3/12$

Mean diameter of pipe D = $\mathbf{D_o - t}$

[Source: BS 9295: 2020 Equations 32a, 33 and 34]

Note: Information on pipes subjected to vacuum pressures in service is not included in this document, further guidance can be sought from BS 9295: 2020 or the pipe manufacturer. The term for short-term vacuum pressure in Equation 32a of BS 9295: 2020 is not therefore shown in Equations 5.5 and 5.6.

Step 6: Calculate initial and long-term deflection

Using Equations 5.7 and 5.8, calculate the initial and long-term deflection.

Initial deflection prior to pressurisation $(\Delta/D)_I = \frac{K_x(D_L p_e + p_s)}{(8(\frac{E_S I}{D^3}) + 0.061E')}$ Eqn (5.7a)

Initial deflection reduced by internal pressurisation

$(\Delta/D)_R = (\Delta/D)_I . D_R = \frac{K_x(D_L p_e + p_s)}{(8(\frac{E_S I}{D^3}) + 0.061E')} . D_R$ Eqn (5.7b)

Long-term deflection $(\Delta/D)_L = \frac{K_x(D_L p_e + p_s)}{8(\frac{E_L I}{D^3}) + 0.061E'} . D_R$ Eqn (5.8)

where:

p_e is pressure due to soil load "overburden pressure" (see Step 2)

p_s is pressure due to traffic loads "surcharge pressure" (see Step 3)

E' is effective overall modulus of soil reaction (see Step 4)

D_R is the rerounding factor calculated by D_R = 1-($\mathbf{p_i}$/40) and P_i is internal water pressure in bar

Second moment of area of the pipe wall I = $\mathbf{t^3}$/12

Mean diameter of pipe D = $\mathbf{D_o}$ **–** t

K_x is deflection coefficient (see step 4)

D_L in equation 5.7a is 1.0

[Source: BS 9295: 2020 Equations 35 and 36]

Note 1: The effect of rerounding is included in Equation 5.8. See Section 3.1.

Note 2: The effect of rerounding applies only where P_i exceeds 3 bar, water pressure is applied within one year of backfilling and depth of no greater than 2.5 m [Source: BS 9295: 2020 7.2.8].

Note 2: In BS 9295: 2020[7], a new term (Δ_0/D) was introduced to the equation for calculation of initial and long-term deflection in pressure and non-pressure pipelines (Equation 35). It is acknowledged that the use of the Marston-Spangler method for plastic pipes leads to a conservative design solution[1,3]. Furthermore, in Section 2, it is explained that field trials in 1980s / 1990s confirmed that measured values of deflection were very conservative compared to calculated values. This new term has the effect of adding a further 0%-5% to the calculated value of deflection, depending on pipe ring stiffness, type of backfill materials and *level of supervision. There is no evidence to suggest that the deflections calculated using Equation 23 of NA 6.2.4 BS EN 1295-1: 1997[8] are falling short of the actual deflections seen in practice. The term (Δ_0/D) is therefore not included in Equations 5.7 and 5.8 presented here.*

Design Check 2

The calculated values of initial and long-term deflection should not exceed the maximum allowable deflection limit for the pipe, $(\Delta/D)_A$ (see 4.2).

If this value is exceeded, the pipe selection and embedment materials should be revisited. Repeat steps 4, 5, and 6. If acceptable, move to Step 7.

Step 7: Calculate stress in the pipe wall

Using Equation 5.9, calculate the stress in the pipe wall.

Design hoop stress $\sigma_c = \frac{(\boldsymbol{p_i} - p_e).D}{2t}$ Eqn (5.9)

where:

p_i is internal water pressure in kN/m^2

p_e is pressure due to soil load "overburden pressure" (see Step 2)

Mean diameter of pipe D = **$\mathbf{D_o}$ –** t

[Source: BS 9295: 2020 Equation 37]

Design Check 3

The calculated value of stress in the pipe wall, σ_c, should not exceed the maximum allowable stress limit for the pipe material, σ_{ca} (see 4.2).

If this value is exceeded, the pipe selection and embedment materials should be revisited. Repeat steps 4, 5, 6, and 7. If acceptable, design is complete.

Note: In the event of a large external pressure on the pipe, the term (p_i-p_e) in Equation 5.9 could indicate wrongly that a larger internal pressure than that stated by the pressure rating (PN) could be applied. The BPF Pipes Group and its members advise that plastic pipes are not operated above their pressure rating (PN).

6. Design calculation – non-pressure pipes

Step 1: Assemble basic data required for design calculation

The data required for pressure pipe design is given below. The data source, symbols and units are given for each parameter in Annex B. **Where these are used in the calculations, they are shown in bold.** The term is not described each time.

Materials / Pipe

- External diameter of pipe D_o
- Pipe wall thickness t
- Mean diameter of pipe D
- Short-term pipe stiffness S_i
- Long-term pipe stiffness S_L
- Modulus of elasticity of pipe material in ring bending – Short-term E_s
- Modulus of elasticity of pipe material in ring bending – Long-term E_L

Embedment

- Native soil type
- Effective width of trench B_d
- Embedment material type
- Degree of compaction of bedding material

Loading

- Depth of cover H
- Unit weight of soil "overburden" γ
- Type of surface surcharge (main road / field and garden)

Step 2: Calculate vertical pressure due to soil load, p_e

(Also called "overburden pressure")

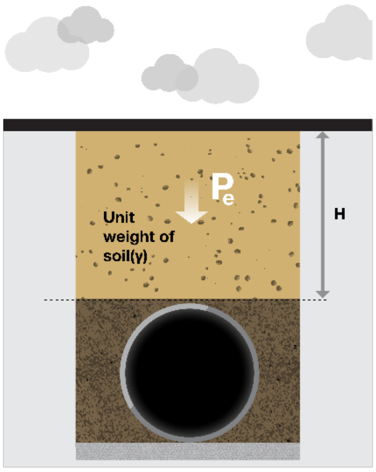
Using Equation 6.1, calculate vertical pressure due to soil load (p_e):

p_e = **Unit weight of soil** x **Depth of cover** = γ.H Eqn (6.1)

[Source: BS 9295: 2020 Equation 27]

Note: In the absence of specific information being available, 19.6 kN/m^2 may be assumed for the soil unit weight [Source: BS 9295:2020 7.2.1.]

Figure 6 Schematic to show vertical pressure due to soil load acting on pipe



Step 3: Establish vertical pressure due to traffic loads (surface surcharge),p_s

(Also called "surcharge pressure")

With knowledge of the **Depth of cover (H)** and **Type of surface surcharge**, use Table 1 (Annex A) to establish vertical pressure due to traffic loads, p_s.

Step 4: Establish embedment properties, E'_2, D_L, E'_3

With knowledge of the **Embedment material type**, use the Table 2 (Annex A) to identify the Embedment Class. *Note: The Embedment Class might be specified in the contract.*

For the Embedment Class and the **Degree of compaction of bedding material (M_p)**, use Table 2 (Annex A) to identify the following:

- K_x Deflection coefficient
- E'_2 Modulus of soil reaction, Embedment
- D_L Deflection Lag Factor

For trench width less than 4.3 times the external pipe diameter (i.e. $\mathbf{B_d} < 4.3\ \mathbf{D_o}$) and with knowledge of the **Native soil type**, use Table 3 (Annex A) to establish E'_3 (Modulus of soil reaction for native soil).

Using Equation 6.2, calculate the effective overall modulus of soil reaction (E'):

$E' = E'_2 \, . \, C_L$ Eqn (6.2)

where $$C_L = \frac{0.985+0.544\left(\frac{B_d}{D_o}\right)}{\left[\left(1.985-0.456\left(\frac{B_d}{D_o}\right)\right).\left(\frac{E'_2}{E'_3}\right)\right]-\left(1-\left(\frac{B_d}{D_o}\right)\right)}$$

[Source: BS 9295: 2020 Equations 29 and 30]

Note: For trench width greater than 4.3 times the external pipe diameter (i.e. $\mathbf{B_d} > 4.3\ \mathbf{D_o}$*),* C_L *is unity (has a value of 1), meaning* E'_3 *does not need to be determined and the effective overall modulus of soil reaction E' is taken to be* E'_2*. (See BS 9295: 2020 7.2.5)*

Step 5: Calculate the factor of safety against buckling

Using Equations 6.3 and 6.4, calculate the short and long-term values of p_{cr} using the **Short- term modulus of elasticity of the material (E_s)** and **Long-term modulus of elasticity of the material (E_L)**.

Short-term critical buckling pressure, $p_{crs} = 0.6.\left(\frac{E_S.I}{D^3}\right)^{0.33}.(E')^{0.67}$ Eqn (6.3)

Long-term critical buckling pressure, $p_{crl} = 0.6.\left(\frac{E_L.I}{D^3}\right)^{0.33}.(E')^{0.67}$ Eqn (6.4)

where:

Second Moment of Area of the pipe wall per unit length $I = \mathbf{t}^3/12$

Mean diameter of pipe $D = \mathbf{D_o - t}$

E' is effective overall modulus of soil reaction (see Step 4)

[Source: BS 9295: 2020 Equation 31]

Design Check 1

Using Equation 6.5, check the factor of safety calculated for the proposed pipeline design against the minimum factor of safety against buckling (see 4.2).

Where the cover depth is less than 1.5m, there is a risk of loss of soil support during work on adjacent utility apparatus. Using Equation 6.6, also check the calculated factor of safety provided by the proposed design against the minimum factor of safety against buckling (see 4.2).

If the calculated factor of safety is lower than the minimum factor of safety against buckling value is exceeded, the pipe selection and embedment materials should be revisited. Repeat steps 4 and 5. If acceptable, move to Step 6.

With soil support, $F_s = \frac{1}{[\left(\frac{p_e}{p_{crl}}\right)+\left(\frac{p_s}{p_{crs}}\right)]}$ Eqn (6.5)

Without soil support, $F_s = \frac{24.(\frac{E_s I}{D^3})}{p_e}$ Eqn (6.6)

where:

p_e is pressure due to soil load "overburden pressure" (see Step 2)

p_s is pressure due to traffic loads "surcharge pressure" (see Step 3)

p_{crs} is short-term critical buckling pressure (see step 5)

p_{crl} is long-term critical buckling pressure (see step 5)

Second moment of area of the pipe wall I = $\mathbf{t}^3/12$

Mean diameter of pipe D = $\mathbf{D_o} - \mathbf{t}$

[Source: BS 9295: 2020 Equations 32a, 33 and 34]

Note: Information on pipes subjected to vacuum pressures in service is not included in this document, further guidance can be sought from BS 9295: 2020 or the pipe manufacturer. The term for short-term vacuum pressure in Equation 32a of BS 9295: 2020 is not therefore shown in Equations 6.5 and 6.6.

Step 6: Calculate initial and long-term deflection

Using Equations 6.7 and 6.8, calculate the initial and long-term deflection.

Initial deflection $(\Delta/D)_i = \frac{K_x(D_L p_e + p_s)}{(8\boldsymbol{S_i} + 0.061E')}$ Eqn (6.7)

Long-term deflection $(\Delta/D)_L = \frac{K_x(D_L p_e + p_s)}{8\boldsymbol{S_L} + 0.061E'}$ Eqn (6.8)

where:

p_e is pressure due to soil load "overburden pressure" (see Step 2)

p_s is pressure due to traffic loads "surcharge pressure" (see Step 3)

E' is effective overall modulus of soil reaction (see Step 4)

K_x is deflection coefficient (see step 4)

D_L in equation 6.7 is 1.0

[Source: BS 9295: 2020 Equation 35]

Note 1: In BS 9295: 2020[7], a new term (Δ_0/D) was introduced to the equation for calculation of initial and long-term deflection in pressure and non-pressure pipelines (Equation 35). It is acknowledged that the use of the Marston-Spangler method for plastic pipes leads to a conservative design solution[1,3]. Furthermore, in Section 2, it is explained that field trials in 1980s / 1990s confirmed that measured values of deflection were very conservative compared to calculated values. This new term has the effect of adding a further 0%-5% to the calculated value of deflection, depending on pipe ring stiffness, type of backfill materials and level of supervision. There is no evidence to suggest that the deflections calculated using Equation 23 of NA 6.2.4 BS EN 1295-1: 1997[8]are falling short of the actual deflections seen in practice. The term (Δ_0/D) is therefore not included in Equations 5.7 and 5.8 presented here.

Design Check 2

The calculated values of initial and long-term deflection should not exceed the maximum allowable deflection limit for the pipe, $(\Delta/D)_A$ (see 4.2).

If this value is exceeded, the pipe selection and embedment materials should be revisited. Repeat steps 4, 5, and 6. If acceptable, design is complete.

Annex A – Supporting Tables

Table 1 Surcharge pressure or Vertical pressure on pipe due to traffic loading as function of depth of cover

[Source: Table 2: BS 9295: 2020]

Depth of cover, H (m)	Surcharge pressure or Vertical pressure on pipe due to traffic loading (kN/m²)	
	Main Roads	**Fields and gardens**
0.5 [A]	-	-
0.6 [A]	-	70
0.7 [A]	-	58
0.8 [A]	-	49
0.9	86	42
1	74	36
1.1	67	32
1.2	62	28
1.3	58	25
1.4	54	22
1.5	51	20
1.6	48	18
1.7	45	16
1.8	43	15
1.9	41	13
2	39	12
2.2	35	10
2.4	33	9
2.6	31	7.7
2.8	29	6.7

3	27	5.9
3.2	26	5.2
3.4	24	4.7
3.6	23	4.2
3.8	22	3.8
4	21	3.4
4.5	19	2.7
5	17	2.2
5.5	16	1.9
6	15	1.6
6.5	14	1.3
7	13	1.2
8	12	0.9
9	11	0.7
10	10	0.6
[A] Pipes with depth of cover less than 0.6 m (fields and gardens) or 0.9 m (roads) need additional protection from vertical loads, such as a concrete slab. Values from Table 2, BS 9295: 2020		

Table 2 Flexible pipe embedment properties

[Source: Table 14 and Table 15: BS 9295: 2020]

Bed and sidefill materials	**Embedment class** **Deflection coefficient K_x**	**Compacted density M_p (%)**	**E'_2 Modulus of soil reaction, Embedment soil (MPa)** [B]	**Deflection lag factor D_L**
Gravel (single size)	Class S1 K_x = 0.083	Self-compacting [A]	10	1.0
Gravel (graded)	Class S2 K_x = 0.083	Uncompacted	3	1.5
		80	5	1.25
		85	7	1.0
		90	10	1.0
Sand and coarse-grained soil with less than or equal to 12% fines	Class S3 K_x = 0.100	85	5	1.5
		90	7	1.25
Coarse-grained soil with more than 12% fines OR fine-grained soil, liquid limit less than 50% medium-to-no plasticity and more than 25% coarse grained materials	Class S4 K_x = 0.100	85	3	1.5
		90	5	1.25
[A] Single-sized granular material, with compaction fraction value of 0.15 or less, capable of filling space under haunches of pipe with low compactive effort. [B] For use in design calculations, E'_2 needs to be converted from MN/m^2 to kN/m^2.				

Table 3a Guide values for soil modulus in various conditions (gravel, sand)

[Source: Table 13: BS 9295: 2020]

Soil type	E'_3 Modulus of soil reaction, Native soil or Spangler Modulus for soils in various conditions (MN/m^2, MPa) [A]				
	Very dense	Dense	Medium dense	Loose	Very loose
Gravel	Over 40	15 to 40	9 to 15	5 to 9	3 to 5
Sand	15 to 20	9 to 15	4 to 9	2 to 4	1 to 2
Clayey / silty sand	10 to 15	6 to 10	2.5 to 6	1.5 to 2.5	0.5 to 1.5
[A] For use in design calculations, E'_3 needs to be converted from MN/m^2 to kN/m^2.					

Table 3b Guide values for soil modulus in various conditions (clay)

[Source: Table 13: BS 9295: 2020]

Soil type	E'_3 Modulus of soil reaction, Native soil or Spangler Modulus for soils in various conditions (MN/m^2, MPa) [A]						
	Very Hard	Hard	Very Stiff	Stiff	Firm	Soft	Very Soft
Clay	11 to 14	10 to 11	6 to 10	4 to 6	3 to 4	1.5 to 3	0 to 1.5
[A] For use in design calculations, E'_3 needs to be converted from MN/m^2 to kN/m^2.							

Annex B – Symbols and data sources

Symbol	Name / Descriptor	Notes	Unit used in design equations in this document	Used in pressure pipe design	Used in non-pressure pipe design
Pipe / pipe materials					
t	Pipe wall thickness	Given in pipe standards. Can also be obtained from specific pipe manufacturer. Typically quoted in mm.	m	✓	✓
D	Mean diameter of pipe	Calculated from $D = D_o - t$	m	✓	✓
D_o	External diameter of pipe	Given in pipe standards. Can also be obtained from specific pipe manufacturer. Typically quoted in mm.	m	✓	✓
S	Pipe stiffness	Also called "Pipe ring stiffness". Calculated from $S= EI/D^3$. Long- and short-term pipe ring stiffness values (S_i and S_L) are dependent upon values of E_L and E_s for the pipe. Stiffness of the pipe is therefore quoted at ambient temperature (20°C).	kN/m^2		✓

E	Modulus of elasticity of pipe material in ring bending	Also called "flexural modulus" or "Young's modulus". E_s – short-term. Typical values PE80 = 900MPa, PE 100 = 1100MPa. E_L – long-term. Typical values PE80 = 130MPa, PE 100 = 160MPa. Time, temperature and material dependent so values generally quoted at ambient temperature (20°C). For operating temperatures greater than 20°C, the pipe manufacturer can advise on values. Typically quoted in MPa.	kN/m^2	✓	✓
I	Second area of moment	Calculated from $t^3/12$.	m^3	✓	
Embedment					
B_d	Effective width of trench		m	✓	✓
E'_3	Modulus of soil reaction, Native soil	Look up value in Table 3. Typically quoted in MPa.	kN/m^2	✓	✓
E'_2	Modulus of soil reaction, Embedment	Also called "Spangler Modulus". Look up value in Table 2. Typically quoted in MPa.	kN/m^2	✓	✓

E′	Modulus of soil reaction, overall	Calculated during design process. Typically quoted in MPa.	kN/m^2	✓	✓
M_p	Degree of compaction of bedding material	Also called "Compacted Density" or "Modified Proctor Density".	%	✓	✓
K_x	Coefficient of active lateral earth pressure, deflection coefficient	Look up value in Table 2.	-	✓	✓
C_L	Leonhardt's Coefficient	Calculated during design process to calculate the overall effective soil modulus.	-	✓	✓
Loading / pipeline operating conditions					
H	Depth of cover from surface to crown of pipe		m	✓	✓
γ	Unit weight of soil	Also called "unit weight of overburden". In the absence of specific soils data, it is normal practice to assume a value of 19.6 kN/m^3 [Source: BS 9295: 2020 7.2.1]	kN/m^3	✓	✓

p_e	Overburden pressure	Also known as "vertical soil pressure". Calculated during design process.	kN/m²	✓	✓
p_i	Internal water pressure	The internal pressure in the pipeline. For design purposes, this should be taken as the Design Pressure (DP), the maximum operating pressure of the systems fixed by the designer. Typically quoted in bar.	kN/m² or bar	✓	
p_s	Vertical pressure due to surcharge	Also known as "vehicle surcharge pressure" Look up value in Table 1	kN/m²	✓	✓
-	Allowable operating pressure	Expected operating condition. Stated by pipeline designer. Typically quoted in bar.			
Design					
D_L	Deflection lag factor	Look up value in Table 2.	-	✓	✓
D_R	Rerounding factor	Equal to (1-p_i/40), where p_i is in bar.	-	✓	
σ_c	Design hoop stress	(Formerly known as combined stress) Calculated during design process. Typically quoted in MPa.	kN/m²	✓	✓

p_{cr}	Vertical pressure due to soil and surcharge, critical buckling pressure	p_{crs} – short-term critical buckling pressure. p_{crl} – long-term critical buckling pressure. Calculated during design process.	kN/m^2	✓	✓
Design criteria					
$\left(\frac{\Delta}{D}\right)_A$	Maximum allowable deflection limit of pipe diameter	See section 4.2.	-	✓	✓
F_s	Minimum Factor of safety against buckling	See section 4.2.	-	✓	✓
σ_{ca}	Allowable stress limit for material	See section 4.2. Typically quoted in MPa.	kN/m^2	✓	✓

Conversions:

- mm to m, multiply by 10^{-3}
- MPa to kPa (kN/m^2), multiply by 10^3
- bar to kPa (kN/m^2), multiply by 100