EN 1993-4-3 (2007) (English): Eurocode 3: Design of steel structures - Part 4-3: Pipelines [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC]

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English Version

Eurocode 3 - Design of steel structures - Part 4-3: Pipelines

Eurocode 3 - Calcul des constructions en acier - Partie 4-3: Tuyauterie

Eurocode 3 - Bemessung und Konstruktion von Stahlbauten - Teil 4-3: Rohrleitungen

This European Standard was approved by CEN on 12 June 2006.

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EUROPEAN COMMITTEE FOR STANDARDIZATION
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EUROPÄISCHES KOMITEE FÜR NORMUNG

Management Centre: rue de Stassart, 36 B-1050 Brussels

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Content

Foreword

This European Standard EN 1993-4-3, "Eurocode 3: Design of steel structures – Part 4.3: Pipelines", has been prepared by Technical Committee CEN/TC250 « Structural Eurocodes », the Secretariat of which is held by BSI. CEN/TC250 is responsible for all Structural Eurocodes.

This European Standard shall be given the status of a National Standard, either by publication of an identical text or by endorsement, at the latest by August 2007, and conflicting National Standards shall be withdrawn at latest by March 2010.

This document supersedes ENV 1993-4-3:1999.

According to the CEN-CENELEC Internal Regulations, the National Standard Organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

Background of the Eurocode programme

In 1975, the Commission of the European Community decided on an action programme in the field of construction, based on article 95 of the Treaty. The objective of the programme was the elimination of technical obstacles to trade and the harmonisation of technical specifications.

Within this action programme, the Commission took the initiative to establish a set of harmonised technical rules for the design of construction works which, in a first stage, would serve as an alternative to the National rules in force in the Member States and, ultimately, would replace them.

For fifteen years, the Commission, with the help of a Steering Committee with Representatives of Member States, conducted the development of the Eurocodes programme, which led to the first generation of European codes in the 1980's.

In 1989, the Commission and the Member States of the EU and EFTA decided, on the basis of an agreement[1) between the Commission and CEN, to transfer the preparation and the publication of the Eurocodes to the CEN through a series of Mandates, in order to provide them with a future status of European Standard (EN). This links de facto the Eurocodes with the provisions of all the Council's Directives and/or Commission's Decisions dealing with European standards (e.g. the Council Directive 89/106/EEC on construction products - CPD - and Council Directives 93/37/EEC, 92/50/EEC and 89/440/EEC on public works and services and equivalent EFTA Directives initiated in pursuit of setting up the internal market).

The Structural Eurocode programme comprises the following standards generally consisting of a number of Parts:

EN1990 Eurocode 0: Basis of structural design
EN1991 Eurocode 1: Actions on structures
EN1992 Eurocode 2: Design of concrete structures
EN1993 Eurocode 3: Design of steel structures
EN1994 Eurocode 4: Design of composite steel and concrete structures

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1) Agreement between the Commission of the European Communities and the European Committee for Standardisation (CEN) concerning the work on EUROCODES for the design of building and civil engineering works (BC/CEN/03/89).

EN1995 Eurocode 5: Design of timber structures
EN1996 Eurocode 6: Design of masonry structures
EN1997 Eurocode 7: Geotechnical design
EN1998 Eurocode 8: Design of structures for earthquake resistance
EN1999 Eurocode 9: Design of aluminium structures

Eurocode standards recognise the responsibility of regulatory authorities in each Member State and have safeguarded their right to determine values related to regulatory safety matters at national level where these continue to vary from State to State.

Status and field of application of Eurocodes

The Member States of the EU and EFTA recognise that EUROCODES serve as reference documents for the following purposes:

- as a means to prove compliance of building and civil engineering works with the essential requirements of Council Directive 89/106/EEC, particularly Essential Requirement N°1 - Mechanical resistance and stability - and Essential Requirement N°2 - Safety in case of fire;
- as a basis for specifying contracts for construction works and related engineering services;
- as a framework for drawing up harmonised technical specifications for construction products (ENs and ETAs)

The Eurocodes, as far as they concern the construction works themselves, have a direct relationship with the Interpretative Documents[2)] referred to in Article 12 of the CPD, although they are of a different nature from harmonised product standards[3)]. Therefore, technical aspects arising from the Eurocodes work need to be adequately considered by CEN Technical Committees and/or EOTA Working Groups working on product standards with a view to achieving full compatibility of these technical specifications with the Eurocodes.

The Eurocode standards provide common structural design rules for everyday use for the design of whole structures and component products of both a traditional and an innovative nature. Unusual forms of construction or design conditions are not specifically covered and additional expert consideration will be required by the designer in such cases.

National Standards implementing Eurocodes

The National Standards implementing Eurocodes will comprise the full text of the Eurocode (including any annexes), as published by CEN, which may be preceded by a National title page and National foreword, and may be followed by a National Annex.

The National Annex may only contain information on those parameters which are left open in the Eurocode for national choice, known as Nationally Determined Parameters, to be used for the design of buildings and civil engineering works to be constructed in the country concerned, i.e. :

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2) According to Art. 3.3 of the CPD, the essential requirements (ERs) shall be given concrete form in interpretative documents for the creation of the necessary links between the essential requirements and the mandates for harmonised ENs and ETAGs/ETAs.

3) According to Art. 12 of the CPD the interpretative documents shall :
(a) give concrete form to the essential requirements by harmonising the terminology and the technical bases and indicating classes or levels for each requirement where necessary ;
(b) indicate methods of correlating these classes or levels of requirement with the technical specifications, e.g. methods of calculation and of proof, technical rules for project design, etc. ;
(c) serve as a reference for the establishment of harmonised standards and guidelines for European technical approvals.
The Eurocodes, de facto, play a similar role in the field of the ER 1 and a part of ER 2.

- values and/or classes where alternatives are given in the Eurocode,
- values to be used where a symbol only is given in the Eurocode,
- country specific data (geographical, climatic, etc), e.g. snow map,
- the procedure to be used where alternative procedures are given in the Eurocode,
- decisions on the application of informative annexes,
- references to non-contradictory complementary information to assist the user to apply the Eurocode.

Links between Eurocodes and harmonised technical specifications (ENs and ETAs)

There is a need for consistency between the harmonised technical specifications for construction products and the technical rules for works[4]. Furthermore, all the information accompanying the CE Marking of the construction products which refer to Eurocodes shall clearly mention which Nationally Determined Parameters have been taken into account.

Additional information specific to EN 1993-4-3

EN 1993-4-3 gives design rules for the structural design of buried pipelines, in particular for the evaluation of the strength, stiffness and deformation capacity.

The rules for local buckling in this part EN 1993-4-3 are in line with those in other pipeline standards. The design critical curvatures according to EN 1993-4-3 are larger than those that could be deduced from EN 1993-1-6. The main reasons are that the loading in buried pipelines is mainly deformation controlled and the consequences of local buckling are less severe than in structures where the loading is mainly load controlled.

It is recognized that many standards exist for the design of pipelines covering many different aspects. Examples are routing, pressure safety systems, corrosion protection, construction and welding, operation and maintenance. For aspects other than the structural design of the pipeline itself, reference is made to the relevant European standards listed in 1.3. This is also the case for elements like valves, fittings, insulating couplings, tees and caps.

Because up till now in EN 1991, no rules exist for actions (loads) on pipelines, reference is made to relevant EN standards on pipelines e.g. EN 1594 on gas transmission pipelines and EN 14161 on pipeline transportation systems for the petroleum and natural gas industries.

National Annex for EN 1993-4-3

This standard gives alternative procedures, values and recommendations for classes with notes indicating where national choices may have to be made. Therefore the National Standard implementing EN 1993-4-3 should have a National Annex containing all Nationally Determined Parameters to be used for the design of buildings and civil engineering works to be constructed in the relevant country.

National choice is allowed in EN 1993-4-3 through paragraphs:

2.3 (2)
[AC1) 3.2 (1)P, (2)P, (3), (4) (AC1]
3.3 (2), (3), (4)
3.4 (3)
4.2 (1)P

[4] see Art.3.3 and Art.12 of the CPD, as well as clauses 4.2, 4.3.1, 4.3.2 and 5.2 of ID 1.

5.1.1 (2), (3), (4), (5), (6), (9), (10), (11), (12), (13)
5.2.3 (2)
5.2.4 (1)

1 General

1.1 Scope

(1) This Part 4-3 of EN 1993 provides principles and application rules for the structural design of cylindrical steel pipelines for the transport of liquids or gases or mixtures of liquids and gases at ambient temperatures, which are not treated by other European standards covering particular applications.

(2) Standards dealing with specific pipeline applications should be used for these purposes, notably

- EN 805 : 2000 for water supply systems (drinking water);
- [AC1) EN 1011, Recommendations for arc welding of steels;
- EN 1090-2, Execution of steel structures and aluminium structures – Technical requirements for steel structures; (AC1]
- EN 1295: 1997 for buried pipelines under various conditions of loading (waste water);
- EN 1594: 2000 for gas supply systems for operating pressures over 16 bar;
- [AC1) EN 10208, Steel pipes for pipelines for combustible fluids (1993):
  Part 1: Pipes of requirement class A;
  Part 2: Pipes of requirement class B; (AC1]
- EN 12007: 2000 for gas supply systems up to and including 16 bar;
- EN 12732: 2000 for welding;
- [AC1) EN 13445, Unfired pressure vessels series; (AC1]
- EN 13941: 2003 for pre-insulated bonded pipe systems for district heating;
- EN 13480: 2002 for industrial pipelines;
- EN 14161: 2004 for pipeline transportation systems for the petroleum and natural gas industries.

(3) Rules related to special requirements of seismic design are provided in EN 1998-4 (Eurocode 8: Part 4 "Design of structures for earthquake resistance: Silos, tanks and pipelines"), which complements the rules of Eurocode 3 specifically for this purpose.

(4) This Standard is restricted to buried pipelines, corresponding to the scope of Eurocode 8 Part 4 for pipelines. It is specifically intended for use on:

- Buried pipelines in settlement areas and in non-settlement areas;
- Buried pipelines crossing dykes, traffic roads and railways and canals.

(5) The design of pipelines involves many different aspects. Examples are routing, pressure safety systems, corrosion protection, construction and welding, operation and maintenance. For aspects other than the structural design of the pipeline itself, reference is made to the relevant European standards listed in 1.2. This is also the case for elements like valves, fittings, insulating couplings, tees and caps.

(6) Pipelines usually comprise several associated facilities such as pumping stations, operation centres, maintenance stations, etc., each of them housing different sorts of mechanical and electrical equipment. Since these facilities have a considerable influence on the continued operation of the system, it is necessary to give them adequate consideration in the design process aimed at satisfying the overall reliability requirements. However, explicit treatment of these facilities, is not included within the scope of this Standard.

(7) Although large diameter pipelines are within the scope of this Standard, the corresponding design criteria should not be used for apparently similar facilities like railway tunnels and large underground gas reservoirs.

(8) The provisions in this Standard are not necessarily complete for particular applications. Where this is the case, additional provisions specific to those applications should be adopted.

(9) This Standard specifies the requirements regarding material properties of plates and welds in terms of strength and ductility. For detailed guidelines and requirements about materials and welding, reference should be made to the relevant standards listed in 1.2.

(10) The scope of this Standard is limited to steel grades with a specified minimum yield strength not exceeding 700 N/mm^2.

1.2 Normative references

This European Standard incorporates, by dated and undated reference, provisions from other standards. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to, or revisions of, any of these publications apply to the European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

AC1⟩ *Texts deleted* ⟨AC1	
AC1⟩ *Texts deleted* ⟨AC1	
EN 1090-2	*Execution of steel structures and aluminium structures – Technical requirements for steel structures;*
AC1⟩ *Texts deleted* ⟨AC1	
Part 1:	*General requirements;*
EN 1594	*Gas supply systems: Pipelines - Maximum Operating Pressure over 16 bar, Functional requirements;*
EN 1990	*Basis of structural design;*
EN 1991	*Actions on structures;*
EN 1993	*Eurocode 3: Design of steel structures;*
Part 1.1:	*General rules and rules for buildings;*
Part 1.3:	*Supplementary rules for cold formed members and sheeting;*
Part 1.6:	*Strength and stability of shell structures;*
Part 1.7:	*Strength and stability of planar plated structures transversely loaded;*
Part 1.8:	*Design of joints;*
Part 1.9:	*Fatigue;*
Part 1.10:	*Material toughness and through-thickness properties;*
Part 1.12:	*Additional rules for the extension of EN 1993 up to steel grades S 700;*
Part 4.1:	*Silos;*
Part 4.2:	*Tanks;*
EN 1997	*Eurocode 7: Geotechnical design;*
EN 1998	*Eurocode 8: Design provisions for earthquake resistance of structures;*
Part 4:	*Silos, tanks and pipelines;*
AC1⟩ *Texts deleted* ⟨AC1	
Part 1:	*Pipes of requirement class A;*
Part 2:	*Pipes of requirement class B;*
AC1⟩ *Texts deleted* ⟨AC1	
Part 1:	*General functional recommendations;*
Part 2:	*Specific functional recommendations for polyethylene;*
Part 3:	*Specific functional recommendations for steel.*
EN 12732	*Gas supply systems - Welding steel pipe work -functional requirements;.*
AC1⟩ *Texts deleted* ⟨AC1	
ISO 1000	*SI Units;*

ISO 3183	*Petroleum and natural gas industries; Steel pipe for pipelines; Technical delivery conditions (1996);*
Part 1:	*Pipes of requirement class A;*
Part 2:	*Pipes of requirements class B;*
Part 3:	*Pipes of requirement class C;*
EN 14870	
Parts 1,2,3	*Induction bends, fittings and flanges for pipeline transportation systems*
ISO 13623	*Petroleum and natural gas industries; Pipeline transportation systems;*
ISO 13847	*Welding steel pipeline (2000);*
Part 1:	*Field welding;*
Part 2:	*Shop welding;*

NOTE 1: EN 1295 is intended for sanitation, and water supply: it is chiefly concerned with principles and equations are presented only in an annex.

NOTE 2: EN 1594 is applicable to new pipelines with a maximum operating pressure (MOP) greater than 16 bar for the carriage of processed, non-toxic and non-corrosive natural gas according to ISO/DIS 13686 in on land gas supply systems. It is prepared by WG 3 Gas Transmission of CEN/TC 234 Gas Supply.

NOTE 3: For more references on gas supply, gas transmission, gas storage, etc., see EN 1594.

NOTE 4: EN 12007 was also prepared by CEN/TC 234.

NOTE 5: EN 13941 is intended for district heating and was prepared by a joint WG of CEN/TC 107 and CEN/TC 267.

NOTE 6: Standard ISO 13623 is prepared by SC2 "Pipeline transportation for the Petroleum and Natural Gas industries", of ISO/TC 67 "Materials, Equipment and Offshore Structures for Petroleum and Natural Gas Industries".

1.3 Assumptions

(1) The general assumptions of EN 1990 apply.

1.4 Distinction between principles and application rules

(1) Reference is made to 1.4 of EN 1993-1-1.

1.5 Definitions

(1) The terms that are defined in EN 1991-1 for common use in the Structural Eurocodes apply to this Part 4-3 of EN 1993.

(2) Unless otherwise stated, the definitions given in ISO 9830 also apply to this Part 4-3.

(3) Supplementary to Part 1 of EN 1993, for the purposes of this Part 4-3, the following definitions apply:

1.5.1 pressure: The gauge pressure of the gas or fluid inside the system, measured in static conditions.

1.5.2 design pressure (DP): The pressure on which the design calculations are based.

1.5.3 operating pressure (OP): The pressure, which occurs within a system under normal operating conditions.

1.5.4 maximum operating pressure (MOP): The maximum pressure at which a system can be operated continuously under normal conditions.

NOTE: Normal conditions are: no fault in any device or stream.

1.5.5 design temperature (DT): The temperature on which the design calculations are based.

1.5.6 operating temperature (OT): The temperature, which occurs within a system under normal operating conditions.

1.6 S.I. units

(1)P S.I. units shall be used in accordance with International Standard ISO 1000.

(2) For calculations, the following consistent units are recommended:

- dimensions and thicknesses	:	m	mm
- unit weight	:	kN/m^3	N/mm^3
- forces and loads	:	kN	N
- line forces and line loads	:	kN/m	N/mm
- pressures and area distributed actions	:	kPa	MPa
- unit mass	:	kg/m^3	kg/mm^3
- acceleration	:	km/s^2	m/s^2
- membrane stress resultants	:	kN/m	N/mm
- bending stress resultants	:	kNm/m	Nmm/mm
- stresses and elastic moduli	:	kPa	MPa (=N/mm^2)

(4) Conversion factors
1 mbar = 100 N/m^2 = 0.1 kPa

1.7 Symbols

The symbols in EN 1990 and EN 1993-1 apply. Further symbols are given as follows:

1.7.1 Roman upper case letters

For the purposes of this Standard, the following symbols apply:

A cross-sectional area of a pipe
C curvature due to bending
D_e external diameter
D diameter of the mid-line of pipe wall
E modulus of elasticity
F normal force in the pipe in longitudinal direction
M bending moment in the pipeline conceived as a beam
M_p plastic moment
M_t torsional moment
N effective normal force in a pipeline
V shear force in the cross-section
Q earth pressure
Q_d directly transmitted earth pressure
Q_i indirectly transmitted earth pressure (support reaction)
Q_{eq} equivalent earth pressure to transform Q_i to a quantity Q_d that gives the same average shell wall moments in the circumferential direction as Q_i
R radius of unstressed bend

1.7.2 Roman lower case letters

a ovalisation parameter
$f_{y.d}$ design value of yield strength
$f_{y.nom}$ nominal value of yield strength
$f_{u.nom}$ nominal value of ultimate tensile strength
$f_{y.min}$ specified minimum yield strength
$f_{y.max}$ maximum value of the yield strength
$f_{u.min}$ specified minimum value for the ultimate tensile strength
$f_{u.max}$ maximum value of the ultimate tensile strength
m shell wall moment per unit width
m_e shell wall moment per unit width at the end of the elastic region
m_p full plastic moment per unit width of shell wall
m_x, m_y shell wall moment per unit width in longitudinal and circumferential direction respectively
n shell wall normal force per unit width
n_p plastic normal force per unit width of shell wall
n_x, n_y normal force per unit width of shell wall in longitudinal and circumferential direction respectively
p_i internal pressure in the pipeline (positive outward)
p_e external pressure on the pipeline (negative when acting inward)
p effective pressure: $p = p_i - p_e$
r radius of a pipe: $r = D/2$
t pipe wall thickness
t_{min} specified minimum wall thickness (nominal wall thickness minus the specified tolerance)
t_r, t_b pipe wall thickness in the straight pipe and the bend respectively

1.7.3 Greek letters

α, β, γ loading angle and bearing angle for Q_d and for Q_i and Q_{eq} respectively
ν Poisson's ratio
γ_F partial factor for actions
γ_M partial factor for material strength
θ circumferential coordinate around shell
σ direct stress
τ shear stress

1.8 Terminology

Supplementary to Part 1 of EN 1993 (and Part 4 of EN 1991), for the purposes of this Part 4.3, the following terminology applies:

1.8.1 emergency: A situation which could affect the safe operation of the pipeline system and/or the safety of the surrounding area, requiring urgent action.

1.8.2 incident: An unexpected occurrence, which could lead to an emergency situation. This includes a leakage of contents.

1.8.3 inspection: The process of measuring, examining, testing, gauging or otherwise determining the status of items of the pipeline system or installation and comparing it with the applicable requirements.

1.8.4 installation temperature: The temperature arising from ambient or installation conditions during laying or during construction.

1.8.5 maintenance: The combination of all technical and associated administrative actions intended to keep an item in, or restore it to, a state in which it can perform its required function.

1.8.6 pig: A device which is driven through a pipeline by the flow of fluid, for performing various internal activities (depending on pig type), such as separating fluids, cleaning or inspecting the pipeline.

1.8.7 pipeline: A system of pipework with all associated equipment and stations up to the point of delivery. This pipework is mainly below ground but includes also above ground parts.

1.8.8 pipeline components: The elements from which the pipeline is constructed. The following are distinct pipeline elements:

- pipe (including cold-formed bends);
- fittings (reducers, tees, factory-made elbows and bends, flanges, caps, welding stubs, mechanical joints etc.);
- constructions, manufactured from the elements referred to above (manifolds, slug catchers, pig launching/receiving stations, metering and control runs etc.);
- ancillaries (valves, expansion joints, insulation joints, pressure regulators, pumps, compressors etc.);
- pressure vessels.

1.8.9 pipeline operator: The private or public organization authorized to design, construct and/or operate and maintain the supply system.

1.8.10 pipework: An assembly of pipes and fittings/

1.8.11 pressure control system: A combined system including pressure regulating, pressure safety and, where applicable, pressure recording and alarm systems.

2 Basis of design

2.1 General

(1)P The design of pipelines shall be in accordance with the provisions in EN 1990 and EN 1991-1.

(2) Actions should be taken from EN 1991 and EN 1997 (Geotechnical design). Because EN 1991 and EN 1997 do not cover all actions that apply to pipelines, actions should also be taken from relevant reference standards, where appropriate.

2.2 Fundamental requirements for pipelines

> **NOTE:** Because of their relevance for pipelines, the following requirements of EN 1991-1 are mentioned here.

(1)P The pipeline shall be designed and constructed in such a way that:

- With acceptable probability, it will remain fit for the use for which it is required, having due regard to its intended life and its cost;
- With appropriate degrees of reliability, it will sustain all actions and other influences likely to occur during the execution and use and have adequate durability in relation to maintenance costs;
- It will not be damaged by events like explosions, impact or consequences of human errors, to an extend disproportionate to the original cause.

(2)P The potential damage of pipelines shall be limited or avoided by appropriate choice of one or more of the following:

- Avoiding, eliminating or reducing the hazards which the structure is to sustain.
- Selecting a structural form that has low sensitivity to the hazards considered.

> **NOTE:** Possibilities to avoid damage (e.g. by excavators and digging machines) are: increasing the wall thickness, increasing the soil cover, applying adequate signalling above ground, and applying concrete cover slabs.

(3)P The above requirements shall be met by the choice of suitable materials, by appropriate design and detailing and by specifying control procedures for production, construction and use, as relevant for the particular pipeline.

2.3 Reliability differentiation

(1) Different levels of reliability may be adopted for different types of pipelines, depending on their possible economic and social consequences of their collapse.

(2) The choice of minimum reliability should be agreed between the designer, the client and the relevant authority.

> **NOTE:** The National Annex may provide the minimum level of reliability for different types of pipelines

(3) Reliability may be expressed in terms of factors for the design and/or quality levels for execution. The recommended values given in this Standard are intended for medium safety requirements.

> **NOTE:** For reliability differentiation, see EN 1998-4. Further guidance can be obtained from relevant standards listed in 1.2.

2.4 Methods of analysis

(1)P The methods of analysis for the structural design of pipelines in this Standard shall be appropriate to the limit state being considered.

2.5 Ultimate limit states

(1)P The basic ultimate limit states shall be taken as:

- Rupture of the pipe wall;
- Collapse (flattening of the cross section);
- Loss of static equilibrium or stability of the pipeline or any of its supports;
- Leakage of the contents, due to other causes than rupture of the pipe wall (e.g., due to insufficient tightness in the connections, or due to corrosion, leading to unacceptable environmental or safety risks).

(2)P In addition other relevant limit states according to EN 1993 shall also be checked.

NOTE: An example of another relevant limit state may be bolt failure in case of flanged connections.

(3) The basic ultimate limit states can be verified by performing the following limit state assessments.

- **LS1: Rupture:** The limit state in which the tensile rupture of the pipe wall occurs.
- **LS2: Plastic strain limitation:** The limit state in which the limiting tensile strain for the pipe wall is exceeded (this limit strain is not a material property but a limitation dependent on the deformation capacity of the pipe wall with its welds).
- **LS3: Deformation:** The limit state for excessive deformation. This can take several forms (e.g. excessive ovality, local buckling, implosion or overall flexural buckling of the pipeline).

  NOTE: In these situations the strains may become excessive and uncontrollable, possibly leading to rupture of the pipe wall.
- **LS4: Fatigue:** The limit state of fracture following many cycles of loading.

  NOTE: Cyclic loading can be divided into two classes according to the limit state reached: low cycle fatigue and high cycle fatigue.
- **LS5: Leakage:** The limit state for leakage of the contents of the pipeline, due to causes other than rupture of the pipe wall (e.g. due to insufficient tightness in the connections, or due to corrosion, or third party activities, if such leakage leads to unacceptable consequences for the safety or health of persons and/or the environment).

(4) In evaluating the limiting tensile strain due consideration should be taken of:

- the presence of imperfections in the pipe material (parent material) and in the joints (welds);
- the different mechanical properties of the parent material and the weld zone.

2.6 Serviceability limit states

(1) The relevant basic criteria for the serviceability limit states should be taken as:

- **LS6: Deformations**, which adversely affect the effective use of the pipeline: ovalisation and deflection.
- **LS7: Vibrations**, which cause discomfort or adversely affect the supports or other parts of the pipeline.
- **LS8: Leakage of the contents**, not leading to unacceptable environmental or safety risks.

3 Properties of materials

3.1 General

(1)P Steels used for pipelines shall have adequate mechanical properties and be suitable for welding.

(2) This Standard specifies the requirements for the material properties of plates and welds in terms of mechanical properties only. For further and more detailed guidance and requirements about materials and welding, reference is made to relevant standards listed in 1.2.

(3) The nominal values of material properties given in this Standard should be adopted as characteristic values in design calculations.

3.2 Mechanical properties of pipeline steels

(1)P The nominal value of the yield strength $f_{y,nom}$ and of the ultimate tensile strength $f_{u,nom}$ shall be taken as the specified minimum values $f_{y,min}$ and $f_{u,min}$ in the relevant standard listed in 1.2. The design values for the yield strength $f_{y,d}$ and for the ultimate tensile strength $f_{u,d}$ shall be taken as:

$$f_{y,d} = f_{y,nom} / \gamma_M \tag{3.1}$$

$$f_{u,d} = f_{u,nom} / \gamma_M \tag{3.2}$$

where γ_M is the partial safety factor.

NOTE: The partial factor γ_M is given in the National Annex. The value γ_M = 1,00 is recommended.

(2)P The maximum values of the yield strength $f_{y,max}$ and the ultimate tensile strength $f_{u,max}$ shall be specified and shall not be more than Δf higher than the specified minimum values of $f_{y,min}$ and $f_{u,min}$.

NOTE: The value Δf for the difference between these strength values may be determined in the National Annex. The value Δf = 50 MPa is recommended.

(3) To ensure adequate ductility, the ratio of ultimate tensile strength to yield strength $f_{u,nom}/f_{y,nom}$ of the steel should not be less than $f_{u,min}/f_{y,min}$.

NOTE: The numerical value yy for the ratio between these strength values may be given in the National Annex. The value $f_{u,min}/f_{y,min}$ = 1,1 is recommended.

(4) The ultimate strain ε_u based on the elongation at failure on a gauge length of $5{,}65\sqrt{A_0}$ where A_o is the original cross-sectional area, should not be less than $\varepsilon_{u,min}$.

NOTE: The value of $\varepsilon_{u,min}$ for the ultimate strain ε_u may be given in the National Annex. The value $\varepsilon_{u,min}$.= 20 % is recommended.

(5)P The material shall have sufficient fracture toughness to avoid brittle fracture at the lowest service temperature expected to occur within the intended life of the structure. Reference is made to EN 1993 part 1.10 and EN 1594.

3.3 Mechanical properties of welds

(1)P It shall be demonstrated that if yielding of the pipe wall occurs, the plastic strains occur in the plate material and not in the weld zone.

(2) It may be assumed that the above requirement is fulfilled if the nominal value of the yield strength of the deposited weld metal is at least x % higher than the specified maximum yield strength of the plate or pipe material.

> **NOTE:** The value x may be given in the National Annex. The value x = 15% is recommended.

(3) The ductility of the deposited weld metal including the effect of allowed weld discontinuities should be such that the weld zone can experience a strain of at least ε%.

> **NOTE:** The value for the strain ε may be given in the National Annex. The value ε = 2% is recommended.

(4) The ultimate strength of the deposited weld metal should be at least y % higher than the specified maximum ultimate strength of the plate or pipe material.

> **NOTE:** The value y may be given in the National Annex. The value y = 15 % is recommended.

3.4 Toughness requirements of plate materials and welds

(1) The requirements for ductility before fracture for the plate materials and welds defined in the preceding sections can be demonstrated by the application of adequate methods as defined in EN 1594.

> **NOTE:** Until there is a European standard on toughness requirements for pipeline plate materials with weld zones and allowed discontinuities, BS 7910: 1999 "Guide on methods for assessing the acceptability of flaws in metallic structures, with amendments October 2000" British Standards Institution, or other national documents can be used.

(2) The provisions of this standard apply only if the quality of the pipe material and welds fulfils the requirements given in EN 1594 or EN 12732 as appropriate.

(3) The limit plastic tensile strain $\varepsilon_{\ell,\mathrm{Rk}}$ (LS2) should be determined as:

$$\varepsilon_{\ell,\mathrm{Rk}} = z\% \qquad \text{[AC1) ... (3.3) (AC1]}$$

> **NOTE:** The value z may be given in the National Annex. The value z = 0,5 % is recommended.

3.5 Fasteners

(1) Fasteners should comply with the provisions in EN 1993-1-8.

3.6 Soil properties

(1) Design values for soil properties (soil engineering parameters) should be obtained according to EN 1997 or other relevant reference standards.

4 Actions

4.1 Actions to be considered

(1) Basic guidance on actions and combinations of actions including accidental and seismic design situations is given in EN 1990 and EN 1991, EN 1997 and EN 1998.

(2) The following actions should be considered, where appropriate:

- Internal pressure;
- External pressure;
- Self weight of the pipeline;
- Self weight of the contents of the pipeline (the product to be transported and the possible presence of other materials e.g. water being used for hydrostatic testing or dust);
- Soil loads;
- Traffic loads;
- Temperature variations;
- Construction loads;
- Imposed deformation: due to differential settlements, mining subsidence and landslides;
- Earthquake loads (reference should be made to Eurocode 8).

(3) Characteristic values of the loads to be considered should be obtained from EN 1991-1 or other relevant reference standards as indicated in 1.1 and 1.2.

4.2 Partial factors for actions

(1)P Partial safety factors shall be based on the required reliability level according to 2.3.

NOTE: The partial safety factors may be given in the National Annex.

4.3 Load combinations for ultimate limit states

(1) The following combinations of design actions for ultimate limit states should be considered:

a) **Internal pressure**: The difference between the maximum internal pressure and the smallest external pressure.

NOTE: This limit state is generally used first for the determination of the wall thickness.

b) **Internal pressure plus other relevant loads**: The internal and external pressure conditions defined in (a), with the other relevant design loads added.

NOTE: This limit state is generally used next to check critical strains.

c) **External pressure plus other relevant loads**: The difference between the maximum external pressure and the smallest internal pressure, with the other relevant design loads added.

NOTE: This limit state is generally used next to check ovalisation, critical strains, local buckling etc.

d) **Temporal variations in pressure plus other relevant design loads**: This case is concerned with cyclic actions on the pipe.

NOTE: This limit state is generally used last to check for fatigue.

4.4 Load combinations for serviceability limit state design

(1) The following combinations of design loads for serviceability limit states should be considered:

e) **Internal pressure plus other relevant loads**: The difference between the maximum internal pressure and the smallest external pressure with the other relevant design loads.

f) **External pressure plus other relevant loads**: The difference between the maximum external pressure and the smallest internal pressure, with the other relevant design loads added.

5 Analysis

5.1 Structural models

5.1.1 Simplified calculation method for ultimate limit state design

NOTE: The simplified calculation method given below is based on the results of an extensive set of more precise calculations.

(1) Provided that the conditions given in (2) to (13) are met, only the load combination (a) of 4.3 (1) need be taken into account (only internal pressure).

(2) The load factors γ_F should be taken as:

$\gamma_F = \gamma_{F1}$ for cross-country pipe lines

$\gamma_F = \gamma_{F2}$ for road, ditch, canal and natural watercourse crossings without flood defences.

$\gamma_F = \gamma_{F3}$ for road, ditch, canal and natural watercourse crossings with flood defences.

[AC1) **NOTE 1:** (AC1] The numerical values for γ_F may be given in the National Annex. The following values are recommended: γ_{F1} = 1,39; γ_{F2} = 1,50; γ_{F3} = 1,82.

[AC1) **NOTE 2:** (AC1] In many pipeline standards the allowable stress = 72 % of yield stress: (1,39 = 1/0,72).

(3) Depending on the design yield strength $f_{y,d}$ the ratio D_e / t_{min} should satisfy the following:

- for $f_{y,d}$ = 240 N/mm^2 : $D_e / t_{min} \leq$ val240 ... (5.1)
- for $f_{y,d}$ = 360 N/mm^2 : $D_e / t_{min} \leq$ val360 ... (5.2)
- for $f_{y,d}$ = 415 N/mm^2 : $D_e / t_{min} \leq$ val415 ... (5.3)
- for $f_{y,d}$ = 480 N/mm^2 : $D_e / t_{min} \leq$ val480 ... (5.4)

NOTE: The values for D_e / t_{min} may be given in the National Annex. The following values are recommended: val240 = 70; val360 = 80; val415 = 92; val480 = 106.

(4) The depth of cover over the top of the pipeline should not exceed D_{cover}. This criterion is not applicable if it can be demonstrated that the effective load at the top of the pipe does not exceed G_{eff}..

NOTE: The values for D_{cover} and G_{eff} may be given in the National Annex. The following values are recommended: D_{cover} = 2,5 m and G_{eff} = 65 kN/m^2.

(5) The specified wall thickness t_{spec} used in the pipe should not be less than $t_{spec,min}$ mm.

NOTE: The value for $t_{spec,min}$ may be given in the National Annex. The following value is recommended: $t_{spec,min}$ = 4,8 mm.

(6) The differential settlements from consolidation should not exceed d_s mm. This differential settlement should increase gradually from zero to the maximum value and back to zero over a distance of at least $2 \bullet \ell\, m$ as indicated in Figure 5.1.

NOTE: The values for d_s and ℓ may be given in the National Annex. The following values are recommended: d_s = 100 mm and ℓ = 20 m.

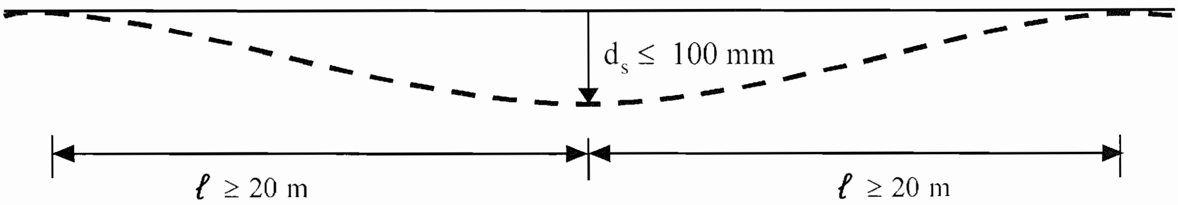


Figure 5.1 Limits on differential settlements with recommended values

(7) The construction settlement should not exceed the values expected in normal pipeline construction practice, in which no special measures have been taken.

(8) The pipeline should not cross potential fracture planes or areas of mining subsidence.

(9) The pipeline section involved should not include bends with a radius smaller than $x\, D_e$.

NOTE: The value for x may be given in the National Annex.

The following value is recommended: x = 20.

(10) The maximum difference between the installation temperature and the maximum or minimum service temperature of the pipeline, as applicable, should not exceed T°C.

NOTE: The value for T may be given in the National Annex. The following value is recommended: T = 35°C.

(11) The overall temperature range should lie between [AC1⟩ T_1°C and T_2°C ⟨AC1]. In the case of frost heave, reference should be made to EN 1594.

NOTE: The values for [AC1⟩ T_1 and T_2 may be given in the National Annex. The following values are recommended: T_1 = - 40°C and T_2 = + 60°C ⟨AC1]

(12) In the case where bends with a radius smaller than $y\, D_e$ are used, the following criteria should be satisfied:

- For pipelines with diameters D_e not greater than [AC1⟩ D_1 ⟨AC1] and with horizontal bends, the maximum difference between [AC1⟩ the installation temperature and the maximum or minimum service temperature of the pipeline should not exceed T_3 °C ⟨AC1].
- For pipelines with D_e < [AC1⟩ D_2 ⟨AC1], the distance between horizontal bends should be greater than ℓ.

NOTE: The values for y, [AC1⟩ T_3, D_1 and ℓ may be given in the National Annex. The following values are recommended: y = 20; T_3 = 20°C; D_1 = 300 mm; D_2 ⟨AC1] = 450 mm and ℓ = 2,0 m.

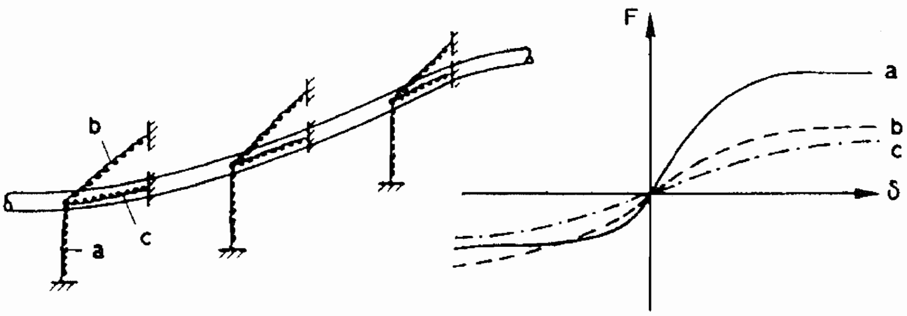
(13) For crossings that are installed by means of boring or jacking, using building pits and where bends with a radius less than $z\ D_e$ are applied in the building pit, the following criteria should be satisfied:

- in the wall thickness calculation of bends a load factor γ_F should be used (as for the crossing).
- for D_e < [AC1⟩ D_2 ⟨AC1] mm the bend should be located at the field side of the building pit.
- for straight pipes the D_e/t_{min} ratio should satisfy:
  - for $f_{y,d}$ = 240 N/mm^2 : $D_e / t_{min} \leq$ val240 ... (5.5)
  - for $f_{y,d}$ = 360 N/mm^2 : $D_e / t_{min} \leq$ val360 ... (5.6)
  - for $f_{y,d}$ = 415 N/mm^2 : $D_e / t_{min} \leq$ val415 ... (5.7)
  - for $f_{y,d}$ = 480 N/mm^2 : $D_e / t_{min} \leq$ val480 ... (5.8)

NOTE: The values for z, γ_F, [AC1⟩ D_2 ⟨AC1] and D_e / t_{min} may be given in the National Annex. The following values are recommended. z = 20; γ_F = 1,82; [AC1⟩ D_2 ⟨AC1] = 450 mm; val240 = 57; val360 = 61; val415 = 70; val480 = 81.

5.1.2 Method of analysis if the conditions for the simplified calculation method are not met

(1) Buried pipelines should be modelled as beams supported by a three-dimensional configuration. In the modelling the springs should represent the properties of the soil, as indicated in Figure 5.2:



(a) lateral vertical earth spring
(b) lateral horizontal earth spring
(c) longitudinal frictional earth spring (also torsional frictional earth spring)

Figure 5.2 Schematic view of a pipeline with "earth springs"

(2) In the analysis, account should be taken of the non-linear character of the various earth springs.

NOTE: In general, a finite element analysis is needed for this system.

(2) The input data for the analysis should be the soil properties, the properties of the pipeline, the imposed settlements (displacements), and other actions.

NOTE: The required properties of the pipeline relate to the bending moment-curvature diagram and, where torsion occurs, the torsion moment-rotation diagram. Expressions to obtain these diagrams are given in annex A.

(4) From the above three-dimensional beam analysis, the following values should be determined at every cross-section of the pipeline:

- bending moment and curvature;
- torsional moment and rotation;
- normal force and lengthening or shortening;
- shear force and shear deformation;
- earth pressure and displacements;
- earth friction and corresponding displacements.

(5) More complete checks of the complete set of deformations may be made using a comprehensive elastic-plastic cross section analysis as set out in annex A.

NOTE: Further guidance and information on limit state design of buried pipelines can be obtained from either annex A; or Gresnigt, A.M. "Plastic Design of Buried Pipelines in Settlement Areas", HERON, Vol. 31, No.4, 1986; or other publications as given in annex C.

5.2 Ultimate limit state verification

5.2.1 LS1: Rupture

(1) The stresses resulting from the analysis should satisfy the von Mises yield criterion:

$$\sigma_{\mathrm{e.Ed}} = \sqrt{\sigma_{\mathrm{x}}^2 + \sigma_{\mathrm{y}}^2 - \sigma_{\mathrm{x}}\sigma_{\mathrm{y}} + 3\tau_{\mathrm{xy}}^2} \leq f_{\mathrm{y,d}} \qquad \text{... (5.9)}$$

5.2.2 LS2: Plastic strain limitation

(1) The maximum tensile strain $\varepsilon_{\max}$ should not exceed the limit strain $\varepsilon_{l,\mathrm{Rk}}$ defined in Section 3.4.

(2) It should be demonstrated that the pipe wall with weld zones and allowed discontinuities has the strain capacity (limit strain) required for the structural analysis.

5.2.3 LS3: Deformation

(1) To prevent snap-through buckling of the cross-section, excessive cross-sectional distortion in the form of ovalisation should be limited.

(2) The ovalisation parameter a, given by:

$$a = \frac{D_{\max} - D_{\min}}{4} \qquad \text{... (5.10)}$$

should be limited to the value $a_{\max}$ given by:

$$a_{\max} = x\, D_e \qquad \text{... (5.11)}$$

NOTE: The value for x may be given in the National Annex. The following value is recommended: x = 0,05.

(3) Local buckling should be assessed using the critical strain ε_{cr}. To evaluate ε_{cr}, the ovalisation due to non-uniform earth pressure should first be evaluated using the parameter a, where a is half of the change in the diameter caused by earth pressure. The value of a should then be used to determine the local radius of curvature r_o at the most compressed part of the circumference, see figure 5.3. The pressure p should be taken as positive in the case of internal pressure and negative in the case of external pressure.

(3) The critical value of the compressive strain ε_{cr} should be obtained from the following:

$$\varepsilon_{cr} = 0{,}25\frac{t}{r_o} - 0{,}0025 + 3000\left(\frac{pr_o}{Et}\right)^2 \frac{|p|}{p} \qquad \text{for } \frac{r_o}{t} \le 60 \qquad \text{... (5.12)}$$

$$\varepsilon_{cr} = 0{,}10\frac{t}{r_o} + 3000\left(\frac{pr_o}{Et}\right)^2 \frac{|p|}{p} \qquad \text{for } \frac{r_o}{t} \ge 60 \qquad \text{... (5.13)}$$

in which:

$$r_o = \frac{r}{1 - \dfrac{3a}{r}} \qquad \text{... (5.14)}$$

(5) It should be shown that:

$$\varepsilon_{max} \le \varepsilon_{cr} \qquad \text{... (5.15)}$$

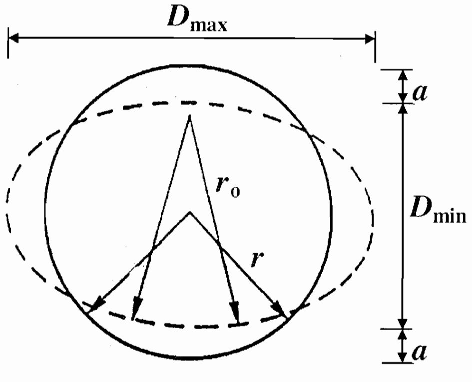


Figure 5.3 Radius r_o in an ovalised cross section

(6) In pipelines under external pressure, the possible collapse (implosion) of the cross-section should be investigated, using the provisions of EN 1993-1-6.

(7) Where there is potential for overall flexural buckling, the design should be assessed using the provisions of EN 1993-1-1.

5.2.4 LS4: Fatigue

(1) The design should satisfy EN 1993-1-9.

NOTE: Other relevant standards for fatigue loading may be referred to in the National Annex.

5.2.5 LS5: Leakage

(1) The consequences of possible leakage of the contents of the pipeline, due to causes other than rupture of the pipe wall (e.g. due to insufficient tightness in the connections, or due to corrosion or third party activities) should be taken into account in design.

(2) Reference should be made to the relevant reference standards.

5.3 Serviceability limit state verifications

(1) The verification of the serviceability limit states LS6, LS7 and LS8 should satisfy the serviceability criteria concerning ovalisation, deflection, vibration and leakage.

(2) Reference should be made to the relevant reference standards.

(3) Criteria for each serviceability limit state (e.g. in relation to pigging requirements) may be agreed between the designer and the client.

(4) Special limits on leakage may be agreed between the designer, the client and the relevant authority, depending on the design conditions (e.g. the nature of the pipeline and its contents and the environment).

6 Structural design aspects of fabrication and erection

(1) The requirements of the relevant application standards should be met.

(2) For fabrication and erection the relevant clauses of EN1090-2 apply.

Annex A: [informative] - Analysis of resistances, deformations, stresses and strains of buried pipelines

A.1 Procedure and scope of analysis

(1) The analysis procedure generally consists of the phases set out in (2) to (7) below.

(2) *Gathering design data.*
Depending on the nature and size of the pipeline transportation system, design data are required for the design and stress engineering processes. These data are defined in detail in relevant reference standards

(3) *Schematization and sectioning of pipeline for analysis.*
For the purpose of analysis, the pipeline, together with the loads acting on it, is schematized and divided into sections.

(4) *Determination of the actions and action combinations to be considered in the analysis and the associated partial factors.*
In principle, each section of the pipeline system should be investigated to determine the effects of the loads referred to in (1). The loads which are relevant to each pipeline section should be determined on this basis. The calculation is based on the design loads. Values of partial factors to be adopted should be taken from relevant reference standards.

(5) *Calculation of forces, moments and relative displacements.*
The pattern and magnitude of the forces and moments, and, where necessary, the deformation of the pipeline should be determined, not only as a function of the length of the completed pipeline system but also, where appropriate, as a function of time. This also applies to forces exerted by the pipeline on its environment (the soil, supports, fixed-point and casing structures, etc.).

(6) *Calculation of stresses, strains and deformation.*
The positive and negative values for stresses and strains which can occur in the walls of the elements of the pipeline system should be determined, where necessary including the range or amplitudes and frequencies of variations in these stresses and/or strains.
Where increased stresses occur in pipeline elements (for example at bends), these should be allowed for in the analysis.
Insignificant stresses, deformations and ranges need not be included in the analysis

(7) *Assessment.*
The stresses, strains, deformations and other values obtained by application of the design loads should not exceed the limiting values.

> **NOTE:** Further information on the subjects in this annex and guidance for practical analysis can be obtained from: A.M. Gresnigt "Plastic Design of Buried Pipelines in Settlement Areas", HERON, Vol. *31, No.4, 1986,* and from other publications as given in annex C.

A.2 Analysis for straight pipes

A.2.1 Definitions of key parameters

Mean diameter $D = D_e - t$

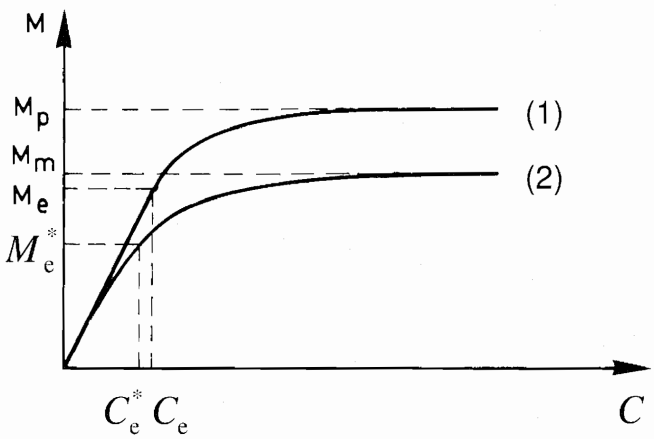
Ovalisation parameter	$a=(D_{max}-D_{min})/4$
Mean radius of a pipe	$r=D/2$
Plastic moment of the pipe cross section	$M_p=4\,r^2 t\,f_y$
Elastic moment of the pipe cross section	$M_e=\pi\,r^2 t\,f_y$
Curvature at the elastic moment of the pipe cross section	$C_e=\dfrac{f_y}{Er}$
Shell wall moment per unit width at the end of the elastic region	$m_e = t^2 f_y/6$
Full plastic moment per unit width of shell wall	$m_p = t^2 f_y/4$
Plastic normal force per unit width of shell wall	$n_p = t f_y$

where f_y is to be taken as $f_{y,d}$

NOTE: For reasons of simplicity, the indexes in this annex are abbreviated by omitting the $_{d,Rd}$ and $_{ESd}$ notations.

A.2.2 Interaction expressions

(1) Figure A.1 gives an indication of the influence of several other actions such as normal force, shear force, internal pressure and earth loading on the moment - curvature diagram for a straight pipe.



1) Without other actions

2) With other actions such as normal force, shear force, internal pressure and earth loading, giving reduced values for the bending moments M_p and M_e (M_m and M_e^* respectively) and a reduced value C_e^* for the curvature C_e.

Figure A.1 Moment - curvature diagrams for a straight pipe

(2) Figure A.2 gives an indication of the possible moment - curvature diagram for a straight pipe loaded with several other actions such as normal force, shear force, internal pressure, earth pressure.

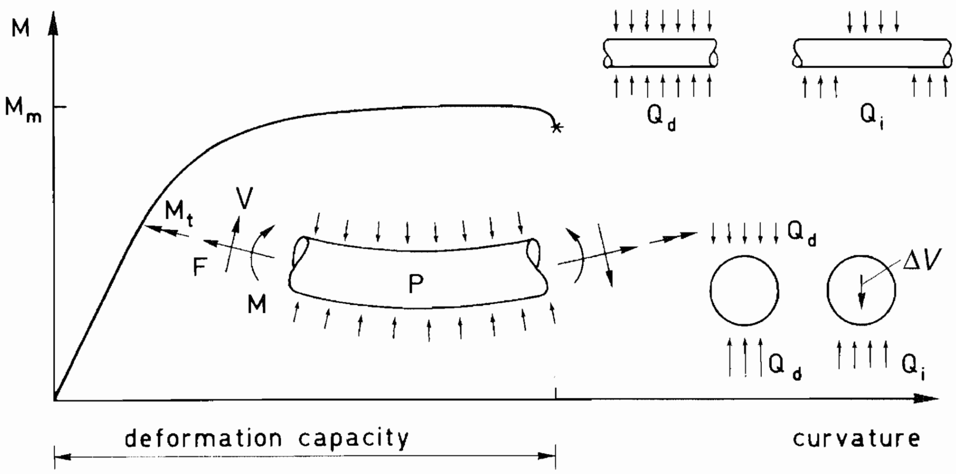


Figure A.2 Moment - curvature diagram for a straight pipe also indicating other actions

(3) Figure A.3 gives the directly transmitted earth pressure Q_d, the indirectly transmitted earth pressure (support reaction) Q_i and the equivalent earth pressure Q_{eq} to transform Q_i to a quantity Q_d that gives the same average shell wall moments in the circumferential direction as Q_i.

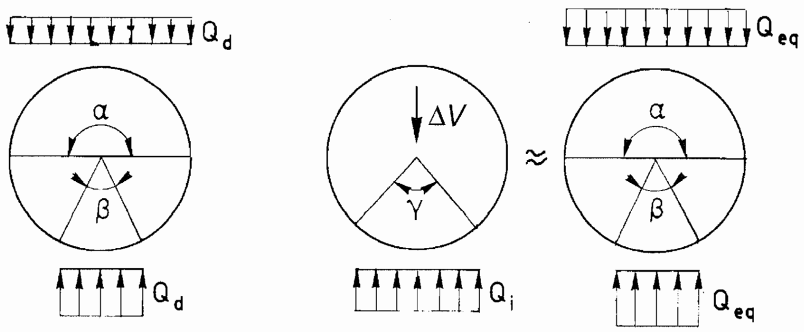


Figure A.3 Earth loads Q_d, Q_1 and Q_{eq} acting on the pipeline cross section

(4) The full plastic bending resistance M_m of the pipe cross-section of a straight pipe loaded by an external axial force F may be obtained from:

$$\frac{M_m}{M_{pdtr}} + \left(\frac{N_m}{N_{pdtr}}\right)^{1,7} = 1 \qquad \text{...(A-1)}$$

$$N_m = F - p\pi r^2 \qquad \text{...(A-2)}$$

where:

M_m is the maximum bending moment at full plasticity;
N_m is the maximum effective normal force at full plasticity.

(5) The resistance under pure bending is given by:

$$M_{pdtr} = M_{pr}\sqrt{1-\left(\frac{V}{V_{pr}}+\frac{M_t}{M_{tpr}}\right)^2} \quad \text{...(A-3)}$$

in which:

$$M_{pr} = g\ h\ M_{pl.Rd} \quad \text{...(A-4)}$$

$$g = \frac{c_1}{6}+\frac{c_2}{3} \quad \text{...(A-5)}$$

$$h = 1-\frac{2}{3}\frac{a}{r} \quad \text{...(A-6)}$$

(6) The resistance under pure axial compression is given by:

$$N_{pdtr} = N_{pr}\sqrt{1-\left(\frac{V}{V_{pr}}+\frac{M_t}{M_{tpr}}\right)^2} \quad \text{...(A-7)}$$

in which:

$$N_{pr} = g\ N_p \quad \text{...(A-8)}$$

(7) The factors modifying the fundamental strength in either bending or compression are:

$$M_{tpr} = g\ M_{tp} \quad \text{...(A-9)}$$

$$M_{tp} = \frac{2}{\sqrt{3}}\pi\ r^2\ t\ f_y \quad \text{...(A-10)}$$

$$M_p = 4\ r^2\ t\ f_y \quad \text{...(A-11)}$$

$$N_p = 2\ \pi\ r\ t\ f_y \quad \text{...(A-12)}$$

$$V_{pr} = g\ V_p \quad \text{...(A-13)}$$

$$V_p = \frac{4}{\sqrt{3}} r\ t\ f_y \quad \text{...(A-14)}$$

$$c_1 = \sqrt{4-3\left(\frac{n_y}{n_p}\right)^2-2\sqrt{3}\frac{|m_y|}{m_p}} \quad \text{...(A-15)}$$

$$c_2 = \sqrt{4 - 3\left(\frac{n_y}{n_p}\right)^2} \qquad \text{...(A-16)}$$

(8) The yield axial force n_y per unit width of shell wall is found as follows:

$$n_y = n_{yq} + n_{yk} + n_{yp} \qquad \text{...(A-17)}$$

$$n_{yq} = 0{,}25\, Q_d + 0{,}125\, Q_i \qquad \text{...(A-18)}$$

$$n_{yk} = 0{,}20 \frac{M_m\ C}{r} \qquad \text{...(A-19)}$$

$$n_{yp} = p\ r \qquad \text{...(A-20)}$$

$$n_p = t\ f_y \qquad \text{...(A-21)}$$

(9) The yield moment m_y per unit width of plate is found as follows:

$$m_y = m_{yq} + m_{yk} + m_{yp} \qquad \text{...(A-22)}$$

$$m_{yk} = 0{,}071 \cdot M_m \cdot C \cdot \eta_o \qquad \text{...(A-23)}$$

$$m_{yp} = -p\ r\ a \qquad \text{...(A-24)}$$

$$m_{yq} = m_{yqd} + m_{yqi} \qquad \text{...(A-25)}$$

$$m_{yqd} = 0{,}25 Q_d\, r\left(1 - 0{,}25\left(\sin\frac{\alpha}{2} + \sin\frac{\beta}{2}\right)\right)\eta_o \qquad \text{...(A-26)}$$

$$m_{yqi} = 0{,}25 Q_i\, r\left(0{,}5 - 0{,}25\ \sin\frac{\gamma}{2}\right)\eta_o \qquad \text{...(A-27)}$$

$$\eta_o = 1 + \frac{a}{r} \qquad \text{...(A-28)}$$

$$m_p = 0{,}25\ t^2 f_y \qquad \text{...(A-29)}$$

(10) The following expressions are of value:

$$Q_{eq} = Q_i \frac{2 - \sin\dfrac{\gamma}{2}}{4 - \sin\dfrac{\alpha}{2} - \sin\dfrac{\beta}{2}} \qquad \text{...(A-30)}$$

$$M_e = \pi\ r^2 t\ f_y \qquad \text{...(A-31)}$$

$$m_e = \frac{1}{6} t^2 f_y \qquad \text{...(A-32)}$$

A.2.3 Moment - curvature diagram

(1) The elastic part of the moment-curvature diagram, as in figure A.2, may be constructed with the following expressions.

$$M = EI_{red} \cdot C \qquad \text{...(A-33)}$$

where

EI_{red} is the reduced (due to ovalisation) bending stiffness of the pipe:

$$EI_{red} = E\pi r^3 t \left(1 - 1.5 \frac{a'}{r}\right) \qquad \text{...(A-34)}$$

a' is the ovalisation at $C = C_e^*$

(2) The elastic-plastic part of the moment-curvature diagram, as in figure A.2, may be constructed with the following expressions.

$$M = M_m \, 0.5 \left(\frac{\theta}{\sin\theta} + \cos\theta\right) \cdot \left(1 - 1.5 \frac{a}{r}\right) \qquad \text{...(A-35)}$$

$$C = 2\frac{\varepsilon}{D} \qquad \text{...(A-36)}$$

$$\varepsilon_y = f_y / E \qquad \text{...(A-37)}$$

$$\mu = \frac{\varepsilon}{\varepsilon_y} \qquad \text{...(A-38)}$$

$$\theta = \arcsin(1/\mu) \quad \text{with} \quad 0 < \theta \leq \pi/2 \quad \text{where} \quad \mu \geq 1 \qquad \text{...(A-39)}$$

where:

M is the bending moment at curvature C;
C is the curvature of the pipe;
θ is a parameter depending on the maximum bending strains in axial direction;
ε is the maximum bending strain in axial direction

NOTE: The elastic part of the moment-curvature diagram ends at $\theta = \pi/2$. The bending moment and curvature at this point are then given by (see also figure A1and A2):

$$M_e^* = \frac{\pi}{4} M_m \qquad \text{...(A-40)}$$

$$C_e^* = 2\frac{\varepsilon_y}{D}\frac{M_m}{M_p} \qquad \text{...(A-41)}$$

A.2.4 Calculation of the ovalisation

(1) At curvatures lower than C_e^*, the ovalisation and strains in axial and circumferential direction can be obtained by applying the theory of elasticity.

(2) At curvatures larger than C_e^*, the ovalisation and strains in axial and circumferential direction should be obtained taking into account the normality principle for deformations.

NOTE: Guidance can be obtained from: A.M. Gresnigt "Plastic Design of Buried Pipelines", HERON, Vol. 31, no.4, 1986, and from other publications as given in Annex C.

NOTE: In the next clauses an approximate method is given, see also NEN 3650.

(3) The ovalisation a is mainly caused by soil pressure, but also bending contributes. The internal pressure reduces ovalisation ("rerounding effect").

(4) The ovalisation a consists of an elastic part a_{el} and a plastic part a_{pl}.

$$a = a_{el} + a_{pl} \quad \text{...(A-42)}$$

(5) The elastic part a_{el} may be calculated as follows.

$$a_{el} = a_{qd-el} + a_{qi-el} + a_{c-el}$$

where:

$a_{qd,el}$ is the ovalisation caused by direct earth pressure as is indicated in Figures A.2 and A.3. The earth pressure on top of the cross section equals the supportive earth pressure.

$$a_{qd,el} = 0{,}5 k_{yd} \frac{Q_d \cdot r^3}{EI_w}(1 + \frac{3a}{r}) \cdot f_{rr} \quad \text{...(A-43)}$$

$a_{qi,el}$ is the ovalisation caused by indirect earth pressure as indicated in Figures A.2 and A.3, e.g. support reactions due to uneven settlements.

$$a_{qi,el} = 0{,}5 k_{yi} \frac{Q_i \cdot r^3}{EI_w}(1 + \frac{3a}{r}) \cdot f_{rr} \quad \text{...(A-44)}$$

$a_{c,el}$ is the ovalisation caused by curvature.

$$a_{c,el} = C^2 \frac{r^5}{d^2}(1 + \frac{3a}{r}) \cdot f_{rr} \quad \text{...(A-45)}$$

where:

k_{yd} is the deflection coefficient dependent on the loading pattern of the direct earth pressure, some values are given in table A.1. See also Figure A.2

k_{yi} is the deflection coefficient dependent on the loading pattern of the indirect soil load, some values are given in table A.1. See also Figure A.2

f_{rr} is a rerounding factor

$$f_{rr} = \frac{p_{cr}}{p_{cr} + p} \qquad \text{...(A-46)}$$

p_{cr} is the theoretical value of the implosion pressure

$$p_{cr} = \frac{3EI_w}{r^3} \qquad \text{...(A-47)}$$

EI_w is the bending stiffness of the pipe wall per unit length (Nmm^2/mm)

$$EI_w = \frac{Et^3}{12(1-\nu^2)} \qquad \text{...(A-48)}$$

C is the curvature

$$C = \frac{M}{EI} = \frac{M}{E \cdot \pi\, r^3 d} \qquad \text{...(A-49)}$$

(6) The equations for the ovalisation $a_{qd\text{-}el}$ and $a_{qi\text{-}el}$ may be applied until the maximum bending moment in the pipe wall in circumferential direction m_{yq} equals m_p. The equation for $a_{c\text{-}el}$ is valid for curvatures up to C_e^*.

(7) If in the cross section both direct earth pressure and indirect earth pressure act, the maximum bending moment follows from

$$m_{yq} = k_{md} \cdot Q_{di} \cdot r \cdot (1+\frac{a}{r}) \cdot f_{rr} \; + \; k_{mi} \cdot Q_{in} \cdot r \cdot (1+\frac{a}{r}) \cdot f_{rr} \qquad \text{...(A-50)}$$

Table A.1 Deflection and moment coefficients for direct and indirect earth pressure
(see also figure A.2)

Deflection coefficient k_{yd} and moment coefficient k_{md} for direct earth pressure				Deflection coefficient k_{yi} and moment coefficient k_{mi} for indirect earth pressure			
α (degrees)	β (degrees)	k_{yd}	k_{md}	α (degrees)	γ (degrees)	k_{yi}	k_{mi}
180	0	0.116	0.294	-	0	0.074	0.239
180	30	0.113	0.235	-	30	0.071	0.179
180	60	0.105	0.189	-	60	0.064	0.134
180	90	0.096	0.157	-	90	0.055	0.102
180	120	0.089	0.138	-	120	0.048	0.083
180	150	0.085	0.128	-	150	0.043	0.073
180	180	0.083	0.125	-	180	0.042	0.070
0	0	0.149	0.318				
30	30	0.143	0.257				
60	60	0.122	0.207				
90	90	0.110	0.169				
120	120	0.096	0.143				
150	150	0.086	0.129				

(8) The plastic part a_{pl} may be calculated as follows.

$$a_{pl} = (a_{qd-pl} + a_{qi-pl} + a_{c-pl}) \cdot (1+\frac{3a}{r}) \qquad \text{...(A-51)}$$

where

$a_{qd\text{-}pl}$ is the plastic part of the ovalisation caused by direct soil load including rerounding.

$a_{qi\text{-}pl}$ is the plastic part of the ovalisation caused by indirect soil load including rerounding.

$a_{c\text{-}pl}$ is the plastic part of the ovalisation caused by the applied curvature including rerounding.

(9) In most cases the earth loads will be such that the resulting stresses are below the yield stress, so that $a_{qd\text{-}pl}$ and $a_{qi\text{-}pl}$ are zero. If not, then a plastic cross sectional calculation is needed to determine $a_{qd\text{-}pl}$ and $a_{qi\text{-}pl}$.

NOTE: Guidance can be obtained from: A.M. Gresnigt "Plastic Design of Buried Pipelines", HERON, Vol. 31, no.4, 1986, NEN3650, and from other publications as given in Annex C.

(10) For $a_{c\text{-}pl}$ the following approximate equation may be applied.

$$a_{c-pl} = -2\,\frac{r^3}{t}\cdot\psi\cdot(C - C_e^*) \qquad \text{...(A-52)}$$

where:

$$\psi = 1 - \left(\frac{0{,}5\cdot c_2}{g}\right)^2 \qquad \text{...(A-53)}$$

NOTE: Because c_2 and g are dependent on the curvature and the ovalisation, an iterative procedure will be needed.

A.2.5 Calculation of the strains

(1) The maximum strain in longitudinal direction may be estimated from

$$\varepsilon_x = \varepsilon_{xC} + \varepsilon_{xN} \qquad \text{...(A-54)}$$

where:

$$\varepsilon_{xC} = \pm C\cdot r \qquad \text{...(A-55)}$$

$$\varepsilon_{xN} = \frac{N}{AE} \qquad \text{...(A-56)}$$

A is the cross sectional area.

(2) The maximum strain $\varepsilon_{y\text{-}max}$ in circumferential direction may be estimated from the following approximate method

$$\varepsilon_{y-max} = \varepsilon_{y-el} + \varepsilon_{y-pl} \qquad \text{...(A-57)}$$

(3) For the elastic part ($\varepsilon_{y\text{-}el} \le \varepsilon_{yield} = f_y/E$):

$$\varepsilon_{y-max} = \varepsilon_{y-el} = \pm\frac{k_{md}}{k_{yd}}\cdot\frac{t}{r^2}\cdot a + \frac{k_{mi}}{k_{yi}}\cdot\frac{t}{r^2}\cdot a + \frac{p\cdot r}{E\cdot t} \qquad \text{...(A-58)}$$

NOTE: The ovalisation at ε_{yield} is called a_{yield}.

(4) For the plastic part ($\varepsilon_{y\text{-pl}} > \varepsilon_{yield} = f_y / E$):

$$\varepsilon_{y-pl} = \pm \left(\frac{a}{a_{yield}} \right)^2 \cdot \varepsilon_{yield} + \frac{p \cdot r}{E \cdot t} \qquad \text{...(A-59)}$$

A.3 Analysis for bends

(1) Reference is made to relevant reference standards and to:

- A.M. Gresnigt "Plastic Design of Buried Pipelines", HERON, Vol. 31, no.4, 1986;
- Other publications as given in Annex C.

Annex B: [informative] - Bibliography to National standards and design guides

BS 8010 (1989-1993) Code of practice for pipelines. *British Standards Institution.*
Part 1: Pipelines on land: general.
Part 2: Pipelines on land: design, construction and installation.
Part 3: Pipelines subsea: design, construction and installation.
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AC1) NEN 3650 (2003-2006) Requirements for pipeline systems
Part 1: General (NEN 3650-1: 2003+A1:2006)
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Issued by NEN (available in Dutch and in English language). (AC1

BS 7910 (1999) "Guide on methods for assessing the acceptability of flaws in metallic structures, with amendments of October 2000", *British Standards Institution.*

API-5L : Specification for Line Pipe.
API-5LX : Specification for high-test Line Pipe.
API-5LS : Specification for spiral welded Line Pipe.
API-1104 : Specification for Field Welding of Pipelines.
API-1105 : Recommended Practice on Construction of steel Pipelines.

Annex C: [informative] - Bibliography

C.1 General bibliography on pipelines

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