Structural design of pressure pipes

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Abstract There exist various methods for structural design of buried pressure pipes. However, it must be remembered that sophisticated design methods needs a significant supervision of the construction work to be reliable. The need for detailed calculations varies for different materials. Ductile iron (DCI) pipes have high strength properties and for most DCI pipe installations a design check against EN 545 is fully sufficient as regards the structural design. Glass fibre reinforced polyester (GRP) pipes have a limited strainability and are thus highly dependent on the quality of the installation work. It is recommendable to check that the combined strain of the load cases which the pipe shall be designed for does not exceed the allowable strain for the pipe material. Polyethylene (PE) and Polyvinylchloride (PVC) pipes are flexible pipes with a high strainability. The allowable working pressure for these pipes will normally be determined by the PN class and the operating temperature and the need for structural design calculations is limited. It is interesting to note that PE pipes which have the lowest strength properties of all of the above mentioned materials have the lowest failure rate. The latter shows that it is not just the tensile strength, but other factors such as strainability and corrosion resistance which affect the structural performance of buried pipelines.
Keywords DCI; GRP; PE;pressure pipes; PVC; structural design

Introduction

Structural design of buried pressure pipes is a quite complex field of engineering which has attracted many engineers and researchers over the years. There exist today various national methods for structural design of buried pipes and attempts have been made to create an unified method within CEN, however with limited progress so far. The reason for the difficulties is mainly that different materials behave differently and need different design considerations. In addition there are established design methods in several countries, which are well recognized in the respective country. The aim of this paper is to describe in general terms the differences in structural design for the most commonly used materials for buried pipelines and give an explanation of the interaction between the soil and the pipe.

The paper describes the basic design principles for the following pressure pipe materials:

– Ductile iron (DCI)
– Glass fibre reinforced polyester (GRP)
– Unplasticized polyvinyl chloride (PVC)
– Polyethylene (PE).

Pipe material properties

General

The material properties of the pipe influences the structural design. Below are shortly mentioned the material properties which have the greatest influence on the structural design for water and sewage pressure pipes.

Elastic contra viscoelastic behaviour

For elastic materials like DCI and steel there is a linear relationship between stress and strain almost up to the yield point of the material. All plastics materials can be classified as viscoelastic materials, which means that a certain creep will take place in the material even

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at lower stress levels. The creep properties will differ considerably between different plastics material. The difference between elastic and viscoelastic behaviour of a material is illustrated by Figure 1.

When subjected to a constant stress, the strain increases by time in a viscoelastic material (the material creeps) while the strain in the elastic material remains constant. On the contrary, a constant strain will give a stress relaxation in a viscoelastic material while the stress will remain in the elastic material.

Strength properties

The materials' abilities to withstand short- and long-term stresses differ considerably. Viscoelastic materials have a significantly higher capability to withstand short-term stresses than long-term stresses. The temperature influence on the strength properties is also significant for most viscoelastic materials (see section below), which is the reason that strength properties stated for plastics material always are related to a given temperature (normally +20^{o}C). Approximate tensile strength properties for the most common pressure pipe material at + 20^{o}C are given in Table 1.

Strainability

The materials' abilities to withstand strain without cracking differ widely. In Table 2 are given approximate strainability figures for the different materials.

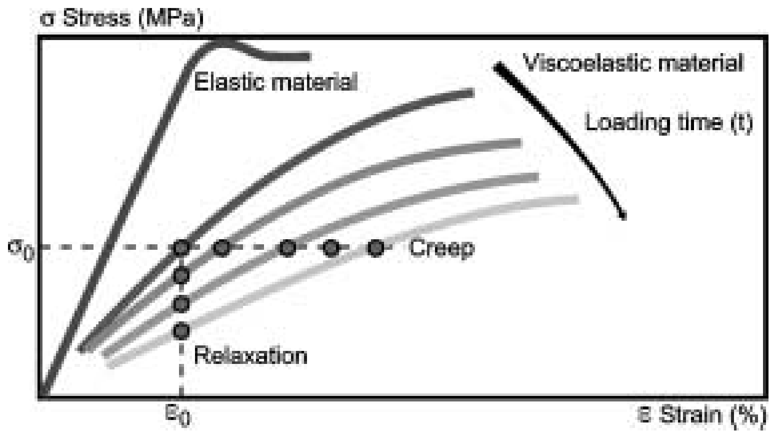

Figure 1 Stress/strain relationship for elastic and viscoelastic materials

Table 1 Approximate tensile strength properties and safety factors for pressure pipes

Material	Tensile strength (N/mm^2)			Safety factor	
	Short-term	Long-term	Allowable stress	Short-term	Long-term
DCI	420	420	140	3	3
GRP*	70–300	***	***	***	***
PE63**	15–23	6.5	5	3–4.6	1.25
PE80**	18–22	8.0	6.3	2.9–3.1	1.25
PE100**	22–25	10	8	2.7–3.1	1.25
PVC	50–60	25	12.5	4–4.8	2

* Tensile strength differs widely depending on laminate build-up.
** Different grades of polyethylene materials.
*** GRP pipes are normally designed according to allowable strain.

Table 2 Strain properties for pressure pipes

Material	Elongation at break (%)	Allowable elongation (%)
DCI	10	0.33
GRP	0.4-2.4	0.4-0.9*
PE63,80,100	>600	5
PVC	25–100	2.5

*Depends on laminate build-up. Stainability properties are often lower in the axial than in the circumferential direction

Rigid contra flexible behaviour

For buried pipes, the ring bending stiffness is of great importance, since it determines the loads and deflection which the pipe will achieve from soil and traffic loads. The ring bending stiffness is normally called the pipe stiffness and defined as follows:

$$S = EI/D^3$$

where S = pipe stiffness (normally expressed in kN/m^2)

E = the short-term modulus of elasticity for the pipe material

I = moment of inertia of the pipe wall ($I=e^3/12$ for a solid wall pipe, where e is the wall thickness)

D = mean diameter of the pipe

The pipe stiffness is thus determined by two factors: the E-modulus, see table 3, and the wall thickness/diameter ratio of the pipe, of which only the first one is a material parameter.

Temperature influence on material properties

Already relatively small temperature increases will reduce the allowable long-term stress value for PE and PVC pipes, while the strength properties for DCI and GRP pipes are not practically affected at moderately temperature increases (up to 40–50°C). Table 4 shows the reduction factors which are to be applied for PE and PVC pipes. Temperatures below +20°C will give an increased tensile strength for PE and PVC pipes.

Corrosion resistance

Plastics pipes will not corrode when buried in ground and do not need to have any corrosion protection layer. DCI pipes have normally an internal and external coating to protect the

Table 3 Approximate *E*-modulus values for different pipe materials.

Material	*E*-modulus at 20°C (MPa)	
	Short-term (3 min)	Long-term (50 years)
DCI	170 000	170 000
GRP*	9 000–15 000	4000–12000
PE63 and 80**	600–900	100–200
PE100	950–1100	200
PVC	3 000	1 000

*Depends on laminate build-up

**Higher values in the interval are valid for high-density PE, lower ones for medium-density PE

Table 4 Pressure reduction factors at temperatures up to 40°C, applicable to a 50-year lifetime

Material	Pressure reduction factors at				
	20 °C	25 °C	30 °C	35 °C	40 °C
PE63,80 and 100 (type A acc.to ISO 4427)	1.0	0.93	0.87	0.80	0.74
PVC		1.0	0.88	0.78	0.70

pipe from corrosion. For large diameter DCI pipes the coating might determine the permissible deflection limit for the pipes.

Design considerations

General

A buried pressure pipe is subjected to internal water pressure and different external loads. The necessity of checking the different possible load cases will to a great extent depend on the pipe material and the pressure class of the pipe. For an elastic material like DCI it has to be checked that the combined stress of the different load cases for which the pipe can be subjected do not exceed the allowable stress. For GRP pipes it has to be checked that the combined strain of the different loadings do not exceed the allowable strain. Thermoplastics pipes, like PE and PVC, show a considerable creep and for those materials a short-term load like water hammer will have little influence on the structural design, since the high short-term safety factors for the materials will allow for additional short-term loads. Below are given the most common load cases which a pressure pipe might be subjected to.

Internal pressure

Pressure pipes are available in different standardized sizes and pressure designations. Plastics pipes are designated in PN classes (like PN4, PN6.3, PN10, PN16 etc.), where the PN number corresponds to the internal pressure in bar which the pipe can withstand without exceeding the allowable stress. The PN number thus corresponds to the internal pressure which the pipe can withstand at +20°C with the applied long-term safety factor, see fig.2.

DCI pipes have the pressure designations K9 and K10. The strength properties of the pipes corresponds to a working pressure of 26-64 bars depending on diameter. In table 5 are given some pipe data for the most common standard pressure pipes.

Water hammer

Water hammer means a short-term pressure fluctuation in the pipe system due to a changed flow caused by start or stop of pumps, closing of valves etc. The magnitude of the fluctuation depends on the water velocity as well as on the material properties of the pipe material. The more flexible a pipe is (low E-modulus, high SDR-ratio), the less stresses will be achieved in the pipe due to water hammer. The pressure surge will therefore be less in a PE pipe system than a corresponding pipe system of DCI or GRP. Since many thermoplastics

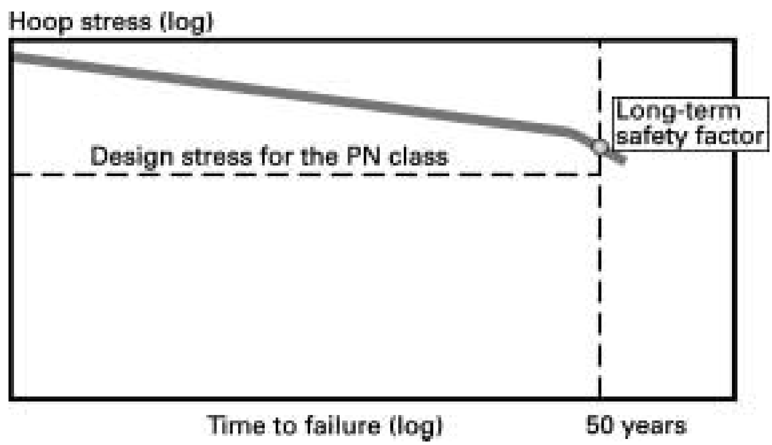

Figure 2 Schematic creep rupture curve for a thermoplastics pipe

Table 5 General pipe properties for different pressure pipe materials

Maximum working pressure (bar)	Material	Pressure designation	SDR-ratio =(*D*+*e*)/*e*	Pipe stiffness *S* (kN/m^2)	Allowable deflection* (%)
	PE63	PN4	26	5**	7
4	PE80	PN4	33	2.5**	7
	GRP	PN6	35–80	1–10	3-4
	PE63	PN6.3	17	19**	7
6	PE80	PN6.3	21	10**	7
	PE100	PN6.3	26	5.5	7
	PVC	PN6.3	41	4	6
	GRP	PN10	35–80	1–10	3-4
	PE63	PN10	11	75**	7
10	PE80	PN10	13.6	38**	7
	PE100	PN10	17	21	7
	PVC	PN10	26	16	6
	DCI	K9	10–93***	18–19500***	0.5–4***
	DCI	K10	10–83***	25–19500***	0.5–4***
	GRP	PN16	36–47**	5–10	3–4
16	PE63	PN16	7.5	275**	7
	PE80	PN16	9	150**	7
	PE100	PN16	11	82	7
	PVC	PN16	17	61	6

* Figures given for PE and PVC pipes are approximate serviceability requirements stated in different national standards. The pipes are able to withstand higher deflections without risk for failure.
** Figures stated are valid for high density PE pipes. Medium density PE pipes give have approximately 10–20 % lower values.
*** The value is depending on the diameter of the pipe.

pipes have a relatively high short-term safety factor, it can be used as a rule of thumb that for thermoplastics pipes water hammer does not need to regarded as a design issue unless the pressure fluctuation exceeds a pressure corresponding to 50% of the pressure class. For GRP pipes the corresponding figure is 25% of the pressure class.

Negative pressure

The pipes ability to withstand negative pressure is directly proportional to the pipe stiffness. The buckling pressure for an unsupported pipe with a circular cross section corresponds to 24*S. An initial ovality will reduce the buckling pressure, but on the contrary the support from the surrounding soil will significantly increase the buckling resistance see Figure 3. Most pressure pipes will have a pipe stiffness considerably higher than 8 kN/m^2 and such pipes are able to withstand a short-term negative pressure down to vacuum without any support from the soil. Installed in soil, the pipe must be able to withstand the combined effect of soil pressure and negative pressure without risk for buckling. A backfill in the trench of friction material (gravel or sand) increases the buckling resistance significantly, giving that a pipe of 4 kN/m^2 stiffness will easily withstand the combined effect of soil pressure and full vacuum without any risk for buckling (safety factor >2).

Soil pressure

When constructing buried pipelines, backfill is placed around the pipe in the trench. Irrespectively of how well the backfill is compacted adjacent to the pipe (sidefill) during installation, further compaction develops with time. Additional settlement then occurs in the sidefill (Figure 4) resulting in an increase in deflection for a flexible pipe. A rigid pipe, which does not noticeably deflect, will be continuously subject to an increased load.

Irrespectively of pipe material, loading/deflection of the pipe during the installation

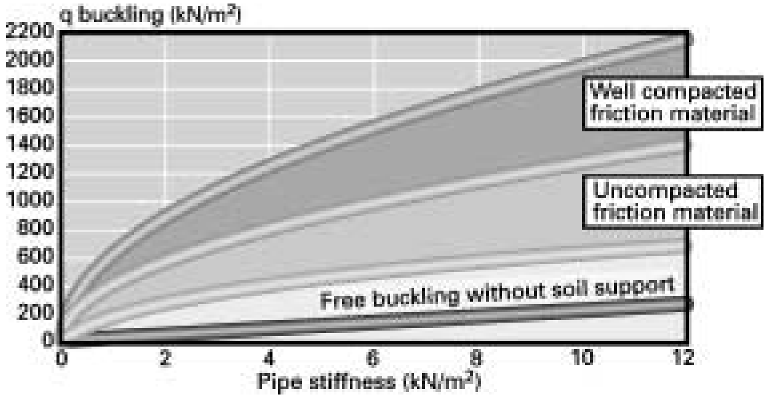

Figure 3 Buckling resistance as a function of pipe stiffness

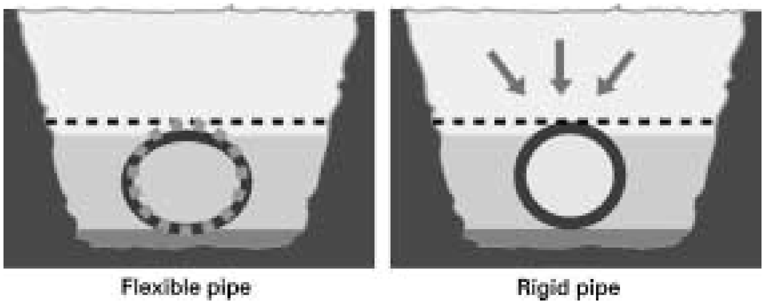

Figure 4 Consolidation of the sidefill gives increased deflection in flexible pipes and an increased load on rigid pipes

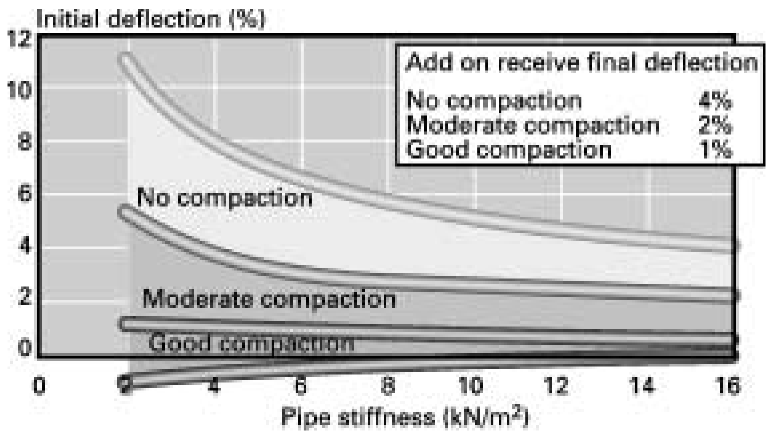

Figure 5 Deflection in practice

phase and further loading/deflection will be achieved by time. However, the magnitude of the loading/deflection is to a large extent dependent on the quality of the compaction of the backfill in the pipe trench. A high degree of compaction of the sidefill will result in low initial deflection and a further small increase in deflection with time. With little or no compaction of the sidefill, a much higher initial deflection will occur as well as a larger increase in deflection with time. Expected deflections as a function of pipe stiffness and quality of installation are given in Figure 5 (Alferink, 1999). As can be seen from Figure 5, reasonably low deflections will be achieved if the pipe stiffness is 4 kN/m^2 or higher. Pressure pipes have normally a much higher stiffness, which is why the effect of soil load does not need to be specifically regarded for most PE and PVC pressure pipes. (The deflection is caused by the settlement of the soil and the stress relaxation in the pipes is significant). For DCI and GRP pipes, which have a more limited deflection capability, the influence of the soil loads must always be regarded. The deflection capability of the different pipe materials as a function of wall thickness/diameter-ratio is shown in Figure 6.

Traffic loads

Traffic loads speed up the settlement in the backfill around the pipe and imply that the final deflection is reached earlier, see Figure 7. However, the final deflection will not be higher for a pipe subjected to traffic loads compared to an identical pipe installation in a non-trafficated area. Traffic loads decrease rapidly with increased laying depth. For flexible pipes, which follow the settlement of the surrounding backfill, traffic loads will in reality not influence the deflection (Teppfa, 1999). In practice, traffic loads will normally only influence the design when such pipes are installed at depths less than around 1 metre.

Thrusts and longitudinal stresses

The forces which the internal water pressure creates in the longitudinal direction of the pipeline have either to be taken by thrust blocks at bends and other discontinuities or to be

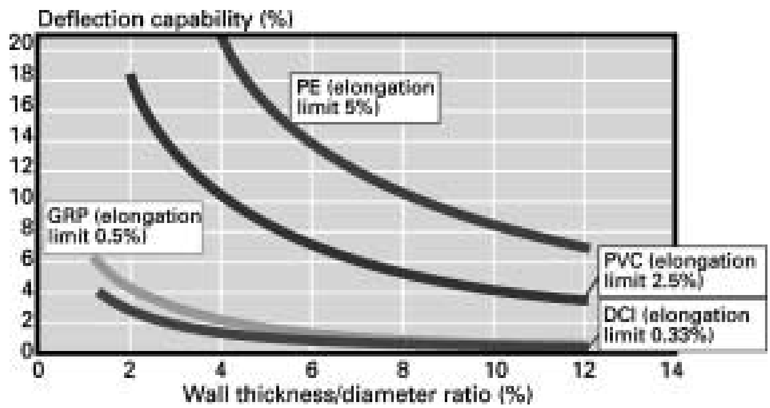

Figure 6 Deflection capability as a function of wall thickness/diameter ratio

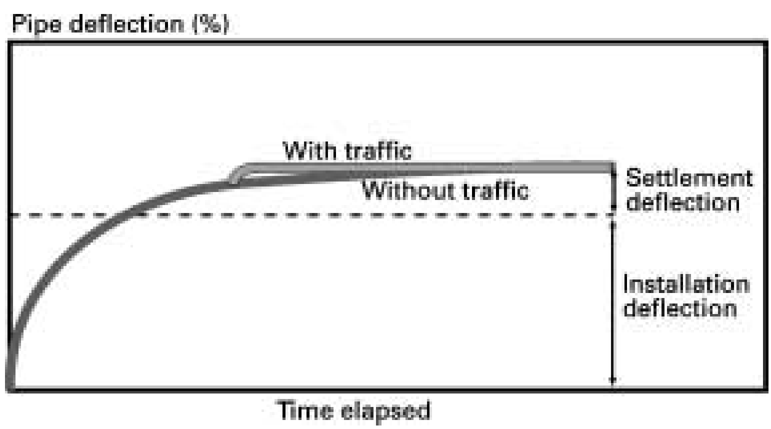

Figure 7 Typical deflection of a buried flexible pipe as a function of time

transferred to the pipe itself by using restrained joints. In addition to the longitudinal stresses caused by the internal pressure, bending stresses may occur due to uneven pipe bed or settlements. The longitudinal stresses will normally be lower than the circumferential ones and do not need to be specifically regarded for thermoplastics pipes in most cases. Many GRP pipes have much lower strength properties in the longitudinal direction than in the circumferential one, and for such pipes a design check must always be executed.

Combined loading considerations

General

The design cases to be considered are depending on the pipe material and the respective load intensities and can be one or more of the following:

- combined circumferential and bending stresses
- combined circumferential and bending strains
- separate consideration of circumferential and bending stresses or strains
- risk for buckling
- thrust and longitudinal stresses.

There exist a number of more and less sophisticated methods for structural design of buried pipes. However, for compliance with reality it is necessary to check that the input data used in the design assumption comply with real ones. Installation of pipes in ground give normally a certain scatter in backfill material properties and compaction which affect the different soil moduli. Therefore, it should be remembered that a sophisticated design method always requires a significant supervision of the installation work to be reliable (Teppfa, 1999).

DCI pipes

For DCI pipes it has to be checked that the total stress of all combined load cases does not exceed the allowable stress. Design advice is given in EN545:1994. The pipe stiffness for a DCI pipe differs considerably with the diameter. Small diameter pipes are very stiff and the pipes are able to withstand high internal pressures under almost all kinds of buried installations. Larger DCI pipes are more flexible but still able to withstand high internal pressures under normal installation conditions. However, the importance of a good installation increases with increased diameter and laying depth. For most installations it is not necessary to carry out detailed structural design calculations. Checking against tables in EN 545 is in most cases sufficient.

GRP pipes

GRP pipes are flexible pipes with a limited strainability. For GRP pipes it is necessary to check that the combined strain of the load cases which the pipe shall be designed for does not exceed the allowable strain. The material properties for the pipes differ considerably with the pipe make and the method of manufacture. For detailed design advice it is recommendable to check information from the respective manufacturer. Re-rounding considerations may be adequate for GRP pipes of lower stiffnesses. GRP pipes are to a great extent depending on the installation work. It should also be noted that the material properties in the axial direction of the pipes often are significantly lower than in the circumferential direction.

PE and PVC pipes

PVC and PE pipes are flexible pipes with a high strainability. Short-term loads will normally be covered by the relatively high short-term safety factor. Limitations for the ovalization of the pipes are normally set by the serviceability of the pipe and not by the allowable strain for the material. The allowable working pressure will in most cases be determined by the pressure class of the pipe and the operating temperature. Detailed design calculations are thus not necessary for normal pipe installations.

Conclusions

DCI pipes are strong pipes for which the structural design seldom constitutes a limiting factor. GRP pipes are able to withstand relatively high pressures, but the pipes are to a great extent dependent on a high quality installation work to ensure a long service life. PVC and specifically PE pipes have compared to DCI and GRP pipes a high strainability. PVC and PE pipes have a significant capability to resist relatively high short-term loads without affecting the long-term strength of the materials. This fact combined with the high strainability of the materials give robust pipes which are able to withstand rough handling and a variable quality of installation work without a noticeably impaired service life. It is interesting to note that different investigations show (Bjorklund, 1994; Stokes, 1999) the lowest failure rates for PE pipes, which have the lowest strength properties of all of the above mentioned pipe materials. The latter shows that it is not just the tensile strength, but other factors as strainability and corrosion resistance which affect the structural performance of buried pipelines.

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