WAVISTRONG™

Engineering Guide

Filament Wound Epoxy Pipeline Systems Series ES/EW/CS

FUTURE PIPE INDUSTRIES

www.futurepipe.com

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Filament Wound Epoxy Pipeline Systems
Series ES/EW/CS

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1. INTRODUCTION

This Wavistrong Engineering Guide provides information for the design, specification and installation of Wavistrong glass fiber reinforced epoxy pipe systems. The diameters range from 25 mm through 1400 mm and is used for aboveground and underground applications.

For detailed product specification, installation information and standard products reference is made to the Wavistrong System Specifications, the Wavistrong Installation Guide and the Wavistrong Product List.
Beyond others, this information can be obtained at www.futurepipe.com.

All conventional methods of calculating stresses in the pipe wall, resulting from internal and external loads, are applicable to the Wavistrong pipe system. The occurring stresses in the structural laminate have to be combined to an equivalent stress and compared with the allowable value of this stress. The allowable equivalent stress has been determined using the Continuum Theory ♪.

The engineering of piping systems is complicated and can be simplified with the aid of calculation programs. As a help for the piping engineer, Future Pipe Industries developed computer programs for the calculation of stresses, strains and deformations for underground and aboveground applications.
On request, computer runs for the calculation of stresses and deformations in a specific underground piping system in accordance with AWWA Manual M45 can be made.
For rigid aboveground applications pipe stress analysis can be made with the aid of computerized flexibility programs.

Although our Engineering Department is able to support the pipe system design with individual calculations as described above, Future Pipe Industries will not act as "designer" as described in ASME B31.3, chapter 1, paragraph 300 (b) (2).

The design of a pipeline system using Wavistrong products means a construction with pipes as well as fittings.

All elements of the system are designed such that the performance requirements of the pipeline are valid for each element of the Wavistrong system.

The choice for one of the possible joining systems will be considered in the design stage of a project. Together with our engineers we can advise an optimal solution.

The possibility of using prefabricated pipeline sections (spools) shall be considered during the design stage of the piping system because of the benefits. The advantages of using spools can be found in the reduced amount of joints to be made in the field, the shorter assembly dimensions, the narrow tolerances and the shortest installation time.

With the knowledge of the system requirements for a pipeline system several questions have to be answered for it to become a successful and fully operational pipeline.

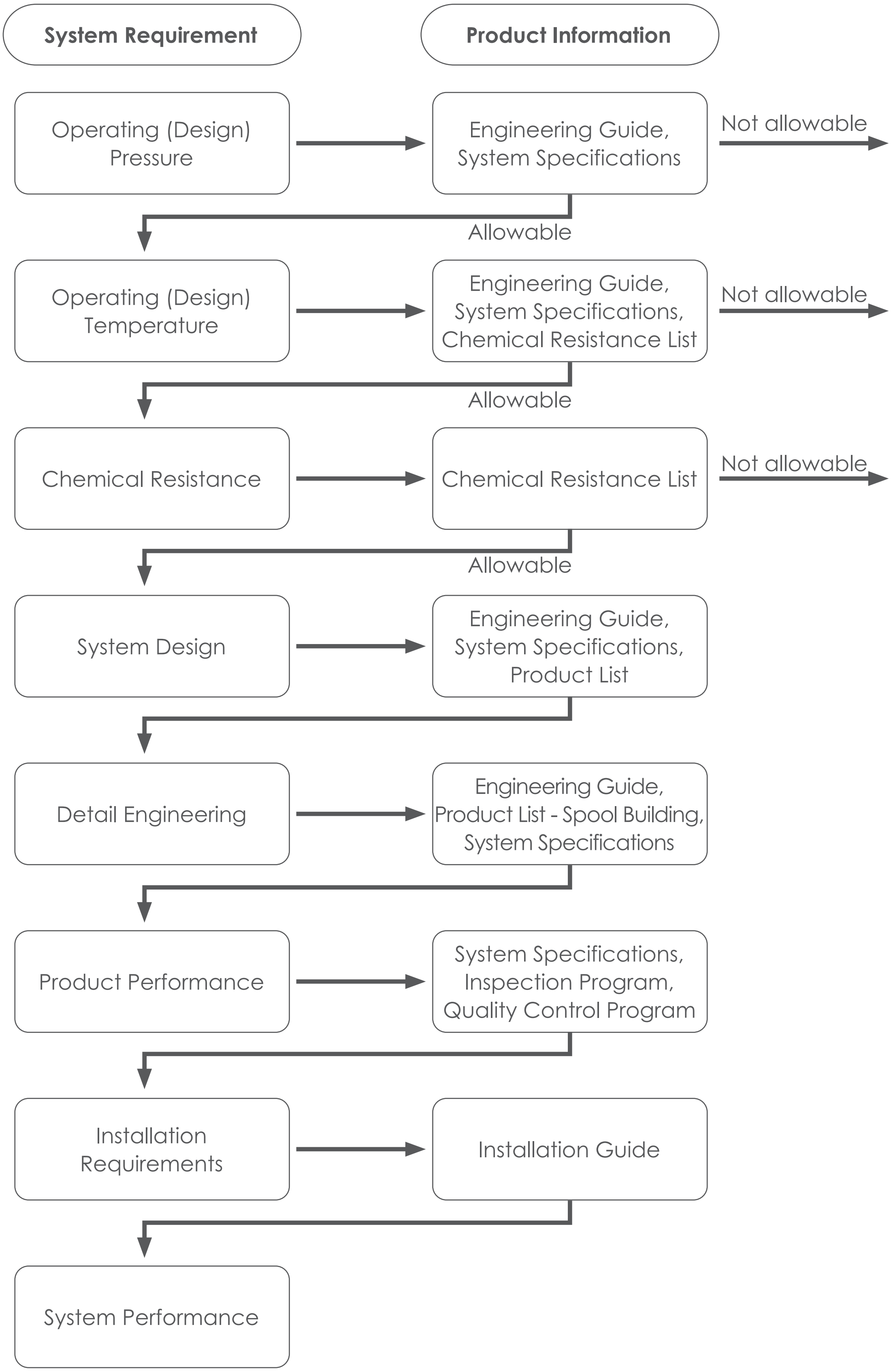
Besides the need for technical discussions many of these questions are answered in our technical literature.

The various subjects of the discussions and the references to the relevant information are given in the following diagram of fig. I.1.

If our product information is not covered by this guide, our engineers will be pleased to assist and inform you about typical design possibilities and latest improvements of Wavistrong.

♪ "Zur Beanspruchung und Verformung von GfK Mehrschichten Verbunden", A. Puck, Kunststoffe-57, Teil 1-II, 1967. Heft 4-7-12.

Fig. I.1. Product information



2. WAVISTRONG INFORMATION

II.1. General

Wavistrong piping systems are manufactured from glass fibers, impregnated with an aromatic - or cyclo aliphatic amine cured epoxy resin.

This thermosetting resin system possesses superior corrosion resistance, together with excellent mechanical, physical and thermal properties.

The glass fiber reinforced epoxy resin piping system resists the corrosive effects of mixtures of low concentrations of acids, neutral or near-neutral salts, solvents and caustics, both under internal and external loads and at temperatures up to 121 °C.

The helical wound continuous glass fibers of the reinforced (structural) wall of the pipes and the fittings are protected on the inner side by the resin-rich liner and on the outer side by the resin topcoat.

II.2. Serial identification

The serial identification consists of two parts, namely:

A. Type identification

The type of product is identified by three alphabetic characters:

1. Type of matrix
   - **E** stands for epoxy resin
   - **C** stands for electrical conductive epoxy resin.
2. Type of application
   - **S** stands for standard
   - **W** stands for potable water
   - **H** high temperature
   - **D** aluminum foil barrier
3. Type of joint
   - **T** stands for tensile resistant
   - **N** stands for non-tensile resistant.

B. Pressure class

This figure indicates the maximum allowable internal pressure (bar) that the product can resist during a life time of 50 years, with a service (design) factor (Sf) of 0.5; this implies a long term safety factor of 2.

Example: Wavistrong Series EST 20 means:
Epoxy resin,
Standard application,
Tensile resistant joining system,
Nominal pressure **20** bar.

For the design of the helical wound pipe it is assumed that for tensile resistant types of joints (identification T)

the ratio $R = \frac{\text{(axial stress)}}{\text{(hoop stress)}} = 0.5$

For non-tensile resistant types of joints (identification N) this ratio R= 0.25.

II.3. Winding angle

Depending on the loading of the system and the pressure class, the continuous glass fiber reinforcement is helical wound under a predetermined angle with the axis of the pipe.
For the various systems the winding angle (ω) is given in table II-a.

Table II-a. Winding angle ω (degrees)

Series	Pressure Class (bar)								
	8	10	12.5	16	20	25	32	40	50
EST	63 °	-	55 °	55 °	55 °	55 °	55 °	55 °	55 °
ESN	-	73 °	-	63 °	63 °	63 °	63 °	-	-

For some applications it can be advantageous to use a different winding angle (ω) in order to obtain specific product characteristics.

II.4. Joining systems

The Wavistrong joining systems are divided into two major groups:

A. Tensile resistant type of joints
These joints can take the full axial load due to internal pressure.

B. Non-tensile resistant type of joints
The axial forces in the system have to be taken by external provisions on the pipeline.

II.4.1. Tensile resistant joints

A. Adhesive bonded conical/cylindrical joint (CJ)
The Wavistrong adhesive bonded conical/cylindrical joint is a rigid type of joining. The joint consists of a slightly conical socket end and a cylindrical spigot end. The socket end is provided with a pipe stop for accurate assembly dimensions (see fig. II.1.).

The adhesive is a two component epoxy resin system, packed in separate containers.

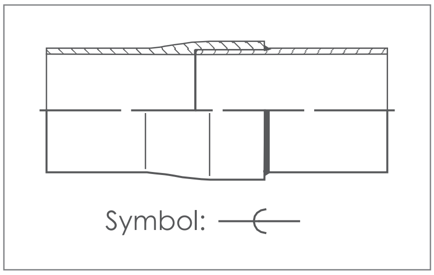


Fig. II.1. CJ

B. Adhesive bonded taper/taper joint (TJ)
An adhesive bonded taper/taper joint is a rigid type of joining. The joint consists of a conical socket - and spigot end
(see fig. II.2.).

The adhesive is a two component epoxy resin system, packed in separate containers.

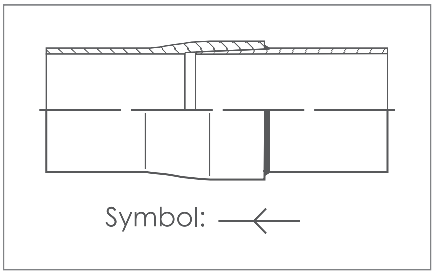


Fig. II.2. TJ

C. Rubber seal lock joint (REKASLJ/RSLJ)

This type of joint consists of an integral filament wound socket end and a machined spigot end. The Reka Ring/ O-Ring seal is positioned on the spigot end. Depending on diameter and pressure class the joint is supplied with one or two locking devices. The locking strip is inserted through an opening in the socket end. The locking strip fits in a circumferential groove on the inside of the socket end and rests against a shoulder on the spigot end (see fig. II.3.).

The Wavistrong rubber seal lock joint allows for some axial movement as well as a certain angular deflection (see table III-g.).

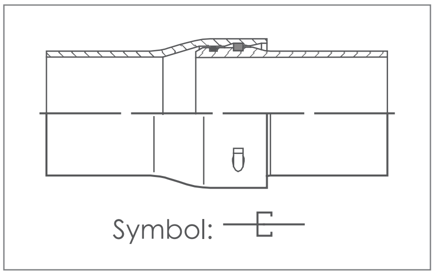


Fig. II.3. RSLJ

D. Laminate joint (LJ)

The preparation of this rigid joint requires good craftsmanship; it is recommended that Future Pipe Industries provides the training and assistance during installation.

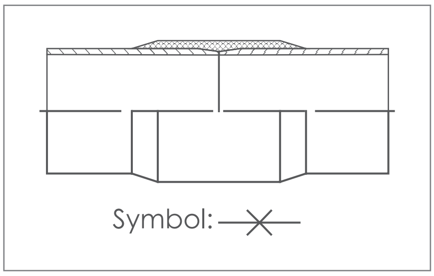


Fig. II.4. LJ

E. Flange joint (FJ)

To enable connection with steel piping and to allow for easy assembling and disassembling of process lines, Wavistrong pipes and fittings can be supplied with flanges, drilled in accordance with ASME, EN or other standards.
Special requirements can also be met upon request.

Wavistrong glass fiber reinforced epoxy flanges are always flat faced. The flange joint is completed by using a gasket (see fig. II.5.).

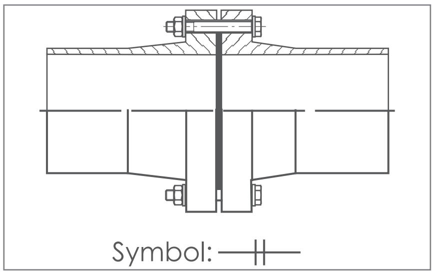


Fig. II.5. FJ

II.4.2. Non-tensile resistant joints

A. Rubber Seal joint (REKASJ/RSJ)

The socket end of this joint is an integral filament wound part of the pipe. The spigot end is a machined part and retains the Reka Ring/ O-Ring seal (see fig. II.6.).

This flexible joint allows for some axial movement of the spigot in the socket and some angular deflection (see table III-g.).

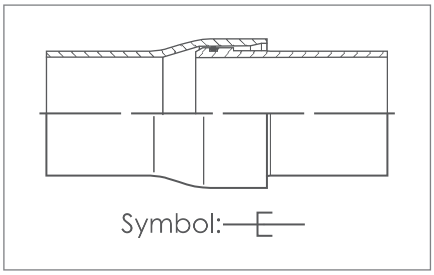


Fig. II.6. RSJ

B. Mechanical coupler (MC)

A mechanical coupler normally consists of a metal casing and a rubber seal.

This joint is available in different versions and is mostly non-thrust resistant. In these joints the sealing is obtained on the (machined) surfaces of plain-ended pipes. The maximum allowable pressure will depend on the type of coupler.

II.5. System data

II.5.1. Pipes

Tables for the mechanical behaviour of the standard pipe series are listed in sections III. and IV.
For the determination of this behaviour, or where these data cannot be used and separate calculations are required, the pipe data from tables II-b. through II-d. and fig. II.7. will provide the necessary information.
Tables II-b. through II-d. give the following data for pipes of the series EST ♪ and ESN ♪:

A. Minimum reinforced wall thickness (T_E)

The minimum reinforced wall thickness is calculated with the ISO-formula:

$$T_E = \frac{ID}{\frac{2 * S_H}{P_N} - 1}$$

(Eq. II.1.)

Where:

T_E = Minimum reinforced wall thickness (mm)
ID = Inner diameter (mm)
S_H = Allowable hoop stress (= HDS, see table II-f.) (N/mm²)
P_N = Nominal pressure. (MPa)

Note: TW = Total wall thickness (mm)
= $T_E + T_L + T_C$

Where:

T_L = Liner thickness = 0.5 mm
T_C = Topcoat thickness = 0.3 mm.

Due to the production process the actual wall thickness may be larger than the calculated minimum value.

B. Mass of the pipe (G_B)

The mass of the pipe is calculated as follows:

$$G_B = \frac{\pi}{4} * (OD^2 - ID^2) * S_L * 10^{-6}$$

(Eq. II.2.)

Where:

G_B = Linear mass of the pipe (kg/m)
OD = Outer diameter (mm)
ID = Inner diameter (mm)
S_L = Laminate density (see table II-j.) (kg/m³)

Note: OD = ID + 2 * T_W

♪ The data in this Engineering Guide for series EST is also valid for series EWT and CST.
The data in this Engineering Guide for series ESN is also valid for series EWN and CSN.

C. Structural wall area (A)

The structural wall area is calculated from:

$$A=\frac{\pi}{4}*(DO^2-DI^2)$$

(Eq. II.3.)

Where:

A = Structural wall area (mm^2)
DO = Structural outer diameter (mm)
DI = Structural inner diameter (mm)

Note: $DO = ID + 2 * (T_L + T_E)$
$DI = ID + 2 * T_L$

D. Linear moment of inertia (I_Z)

The linear moment of inertia is obtained from the following formula:

$$I_Z=\frac{\pi}{64}*(DO^4-DI^4)$$

(Eq. II.4.)

Where:

I_Z = Linear moment of inertia (mm^4)
DO = Structural outer diameter (see Eq. II.3.) (mm)
DI = Structural inner diameter (see Eq. II.3.) (mm)

E. Radius of inertia (I_R)

The radius of inertia is calculated from the following equation:

$$I_R=\sqrt{\frac{I_Z}{A}}$$

(Eq. II.5.)

Where:

I_R = Radius of inertia (mm)
I_Z = Linear moment of inertia (see Eq. II.4.) (mm^4)
A = Structural wall area (see Eq. II.3.) (mm^2)

F. Bore area (A_B)

The bore area of the pipe is:

$$A_B=\frac{\pi}{4}*ID^2$$

(Eq. II.6.)

Where:

A_B = Bore area (mm^2)
ID = Inner diameter (mm)

G. Moment of resistance to bending (W_B)

For the calculation of the moment of resistance to bending the following formula is used:

$$W_B = \frac{\pi}{32} * \frac{(DO^4 - DI^4)}{DO}$$

(Eq. II.7.)

Where:

W_B = Moment of resistance to bending (mm^3)
DO = Structural outer diameter (see Eq. II.3.) (mm)
DI = Structural inner diameter (see Eq. II.3.) (mm)

Note: $W_W = 2 * W_B$

Where:

W_W = Moment of resistance to torsion (mm^3).

H. Mass of the pipe content (G_V)

The values referred to in table II-d. are calculated with the following equation:

$$G_V = \frac{\pi}{4} * ID^2 * S_V * 10^{-6}$$

(Eq. II.8.)

Where:

G_V = Linear mass of the pipe content (kg/m)
ID = Inner diameter (mm)
S_V = Density of fluid (kg/m^3)

Table II-b-1. Pipe data for series EST

Series	Inner Diameter	Reinforced Wall Thickness	Linear Mass of the Pipe	Structural Wall Area	Linear Moment of Inertia	Radius of Inertia	Bore Area	Moment of Resistance to Bending
	ID (mm)	T_E (mm)	G_B (kg/m)	A *10² (mm²)	I_z *10⁴ (mm⁴)	I_R (mm)	A_B *10² (mm²)	W_B *10³ (mm³)
EST 8	350	2.8	7.4	31.1	4869.9	125.1	962.1	273.1
	400	3.2	9.4	40.6	8299.0	142.9	1256.6	407.4
	450	3.6	11.6	51.4	13282.4	160.7	1590.4	579.8
	500	4.0	14.1	63.5	20231.2	178.6	1963.5	794.9
	600	4.8	19.7	91.4	41909.9	214.2	2827.4	1372.7
	700	5.6	26.3	124.3	77588.3	249.8	3848.5	2178.8
	750	6.0	29.9	142.7	102217.7	267.6	4417.9	2679.4
	800	6.5	34.3	164.9	134409.2	285.5	5026.5	3302.4
	900	7.3	42.8	208.3	214831.9	321.1	6361.7	4692.7
	1000	8.1	52.2	256.8	326870.3	356.8	7854.0	6426.9
	1200	9.7	73.9	368.9	676034.9	428.1	11309.7	11078.9
	1400	11.3	99.3	501.4	1250106.5	499.3	15393.8	17562.6
			5					
EST 12.5	250	2.5	4.9	19.9	1599.5	89.6	490.9	125.0
	300	3.0	6.7	28.7	3310.1	107.5	706.9	215.6
	350	3.5	8.9	39.0	6123.8	125.3	962.1	342.1
	400	4.0	11.3	50.9	10435.8	143.2	1256.6	510.3
	450	4.5	14.0	64.4	16702.4	161.1	1590.4	726.2
	500	5.1	17.3	81.1	25964.7	178.9	1963.5	1015.8
	600	6.1	24.3	116.3	53606.1	214.7	2827.4	1748.4
	700	7.1	32.5	157.9	99002.4	250.4	3848.5	2768.5
	750	7.6	37.0	181.1	130303.3	268.2	4417.9	3401.3
	800	8.1	41.8	205.9	168498.1	286.1	5026.5	4123.8
	900	9.1	52.4	260.2	269409.0	321.8	6361.7	5861.8
	1000	10.1	64.0	320.8	410021.8	357.5	7854.0	8030.2
	1200	12.1	90.9	461.1	848356.3	428.9	11309.7	13848.5
EST 16	200	2.5	3.9	16.0	827.5	72.0	314.2	80.3
	250	3.2	5.9	25.6	2064.5	89.9	490.9	160.4
	300	3.8	8.1	36.4	4226.3	107.8	706.9	273.9
	350	4.4	10.7	49.1	7757.7	125.7	962.1	431.2
	400	5.1	13.9	65.1	13415.2	143.6	1256.6	652.5
	450	5.7	17.2	81.8	21325.3	161.5	1590.4	922.4
	500	6.3	20.9	100.4	32304.4	179.4	1963.5	1258.0
	600	7.6	29.7	145.3	67287.9	215.2	2827.4	2184.0
	700	8.9	40.0	198.5	125057.5	251.0	3848.5	3479.6
	750	9.5	45.5	227.0	164115.2	268.9	4417.9	4262.7
	800	10.1	51.4	257.4	211676.1	286.8	5026.5	5155.3

Series	Inner Diameter ID (mm)	Reinforced Wall Thickness T_E (mm)	Linear Mass of the Pipe G_B (kg/m)	Structural Wall Area A *10² (mm²)	Linear Moment of Inertia I_z *10⁴ (mm⁴)	Radius of Inertia I_R (mm)	Bore Area A_B *10² (mm²)	Moment of Resistance to Bending W_B *10³ (mm³)
EST 20	150	2.4	2.8	11.6	340.3	54.2	176.7	43.7
	200	3.3	4.9	21.2	1105.3	72.2	314.2	106.5
	250	4.1	7.3	32.9	2673.5	90.2	490.9	206.3
	300	4.9	10.1	47.1	5509.4	108.2	706.9	354.5
	350	5.7	13.5	63.9	10161.4	126.1	962.1	560.8
	400	6.5	17.3	83.2	17276.9	144.1	1256.6	834.6
	450	7.3	21.6	105.1	27602.1	162.1	1590.4	1185.7
	500	8.1	26.3	129.6	41982.1	180.0	1963.5	1623.4
	600	9.8	37.6	188.1	87719.2	216.0	2827.4	2826.9
	700	11.4	50.5	255.1	161900.3	251.9	3848.5	4473.6
	750	12.2	57.6	292.5	213032.5	269.9	4417.9	5494.8
	800	13.0	65.3	332.4	275414.8	287.8	5026.5	6660.6
EST 25	100	2.4	1.9	7.8	104.2	36.6	78.5	19.7
	125	2.6	2.5	10.5	217.2	45.5	122.7	33.1
	150	3.1	3.5	15.0	445.7	54.5	176.7	56.7
	200	4.1	5.8	26.4	1389.7	72.5	314.2	132.9
	250	5.1	8.8	41.0	3365.4	90.6	490.9	257.7
	300	6.1	12.3	58.9	6940.7	108.6	706.9	443.2
	350	7.1	16.4	79.9	12808.6	126.6	962.1	701.5
	400	8.2	21.4	105.4	22072.7	144.7	1256.6	1057.6
	450	9.2	26.7	133.0	35225.8	162.7	1590.4	1500.9
	500	10.2	32.7	163.8	53531.0	180.8	1963.5	2053.4
	600	12.2	46.3	235.0	110509.1	216.8	2827.4	3534.0
EST 32	80	2.4	1.5	6.3	54.7	29.5	50.3	12.8
	100	2.6	2.0	8.5	113.6	36.6	78.5	21.4
	125	3.2	3.0	13.0	271.2	45.7	122.7	41.0
	150	3.8	4.1	18.5	553.9	54.7	176.7	69.8
	200	5.1	7.1	33.0	1754.4	72.9	314.2	166.1
	250	6.4	10.8	51.8	4288.8	91.0	490.9	325.2
	300	7.7	15.2	74.7	8900.8	109.2	706.9	562.6
	350	9.0	20.5	101.8	16499.9	127.3	962.1	894.3
	400	10.3	26.5	133.1	28160.8	145.5	1256.6	1335.9

Series	Inner Diameter ID (mm)	Reinforced Wall Thickness T_E (mm)	Linear Mass of the Pipe G_B (kg/m)	Structural Wall Area A $*10^2$ (mm^2)	Linear Moment of Inertia I_z $*10^4$ (mm^4)	Radius of Inertia I_R (mm)	Bore Area A_B $*10^2$ (mm^2)	Moment of Resistance to Bending W_B $*10^3$ (mm^3)
EST 40	50	1.8	0.8	3.0	10.4	18.7	19.6	3.8
	65	2.4	1.3	5.2	30.2	24.2	33.2	8.5
	80	2.6	1.6	6.8	59.7	29.6	50.3	13.9
	100	3.3	2.5	10.8	147.2	36.9	78.5	27.4
	125	4.1	3.7	16.8	354.9	46.0	122.7	52.9
	150	5.0	5.3	24.5	746.2	55.2	176.7	92.7
	200	6.6	8.9	43.0	2321.3	73.4	314.2	216.7
	250	8.3	13.7	67.6	5688.4	91.7	490.9	425.1
	300	9.9	19.3	96.7	11694.9	110.0	706.9	729.1
	350	11.6	26.1	132.1	21737.3	128.3	962.1	1161.9
	400	13.2	33.7	171.8	36872.7	146.5	1256.6	1725.4
EST 50	25	1.8	0.4	1.6	1.5	9.8	4.9	1.0
	40	1.8	0.6	2.4	5.6	15.1	12.6	2.5
	50	2.1	0.9	3.5	12.4	18.8	19.6	4.5
	65	2.7	1.4	5.8	34.4	24.3	33.2	9.6
	80	3.3	2.0	8.7	77.8	29.8	50.3	17.8
	100	4.2	3.1	13.9	192.3	37.2	78.5	35.2
	125	5.2	4.6	21.4	461.9	46.4	122.7	67.7
	150	6.3	6.5	31.1	964.5	55.7	176.7	117.9
	200	8.3	11.1	54.6	2993.1	74.1	314.2	275.1
	250	10.4	17.0	85.4	7306.3	92.5	490.9	537.6
	300	12.5	24.2	123.1	15148.6	110.9	706.9	929.4
	350	14.6	32.7	167.7	28062.3	129.4	962.1	1476.2
	400	16.7	42.5	219.1	47870.0	147.8	1256.6	2204.0

Table II-c. Pipe data for series ESN

Series	Inner Diameter	Reinforced Wall Thickness	Linear Mass of the Pipe	Structural Wall Area	Linear Moment of Inertia	Radius of Inertia	Bore Area	Moment of Resistance to Bending
	ID (mm)	T_E (mm)	G_B (kg/m)	A *10² (mm²)	I_z *10⁴ (mm⁴)	I_R (mm)	A_B *10² (mm²)	W_B *10³ (mm³)
ESN 10	450	3.3	10.8	47.1	12151.4	160.6	1590.4	531.1
	500	3.6	12.9	57.1	18164.5	178.4	1963.5	714.9
	600	4.3	17.9	81.8	37450.9	214.0	2827.4	1228.7
	700	5.1	24.2	113.1	70510.1	249.7	3848.5	1982.8
	750	5.4	27.2	128.3	91776.3	267.4	4417.9	2409.5
	800	5.8	30.9	147.0	119621.2	285.3	5026.5	2944.2
	900	6.5	38.5	185.3	190781.1	320.9	6361.7	4174.6
	1000	7.2	46.9	228.0	289770.8	356.5	7854.0	5707.5
	1200	8.6	66.1	326.8	597330.8	427.7	11309.7	9813.3
	1400	10.0	88.6	443.3	1103221.6	498.9	15393.8	15527.4
ESN 16	350	2.8	7.4	31.1	4869.9	125.1	962.1	273.1
	400	3.2	9.4	40.6	8299.0	142.9	1256.6	407.4
	450	3.6	11.6	51.4	13282.4	160.7	1590.4	579.8
	500	4.0	14.1	63.5	20231.2	178.6	1963.5	794.9
	600	4.8	19.7	91.4	41909.9	214.2	2827.4	1372.7
	700	5.6	26.3	124.3	77588.3	249.8	3848.5	2178.8
	750	6.0	29.9	142.7	102217.7	267.6	4417.9	2679.4
	800	6.5	34.3	164.9	134409.2	285.5	5026.5	3302.4
ESN 20	200	2.4	3.8	15.3	793.2	71.9	314.2	77.1
	250	2.5	4.9	19.9	1599.5	89.6	490.9	125.0
	300	3.0	6.7	28.7	3310.1	107.5	706.9	215.6
	350	3.5	8.9	39.0	6123.8	125.3	962.1	342.1
	400	4.0	11.3	50.9	10435.8	143.2	1256.6	510.3
	450	4.5	14.0	64.4	16702.4	161.1	1590.4	726.2
	500	5.1	17.3	81.1	25964.7	178.9	1963.5	1015.8
	600	6.1	24.3	116.3	53606.1	214.7	2827.4	1748.4
ESN 25	200	2.5	3.9	16.0	827.5	72.0	314.2	80.3
	250	3.2	5.9	25.6	2064.5	89.9	490.9	160.4
	300	3.8	8.1	36.4	4226.3	107.8	706.9	273.9
	350	4.4	10.7	49.1	7757.7	125.7	962.1	431.2
	400	5.1	13.9	65.1	13415.2	143.6	1256.6	652.5
	450	5.7	17.2	81.8	21325.3	161.5	1590.4	922.4
	500	6.3	20.9	100.4	32304.4	179.4	1963.5	1258.0
	600	7.6	29.7	145.3	67287.9	215.2	2827.4	2184.0

Series	Inner Diameter	Reinforced Wall Thickness	Linear Mass of the Pipe	Structural Wall Area	Linear Moment of Inertia	Radius of Inertia	Bore Area	Moment of Resistance to Bending
	ID (mm)	T_E (mm)	G_B (kg/m)	A $*10^2$ (mm^2)	I_z $*10^4$ (mm^4)	I_R (mm)	A_B $*10^2$ (mm^2)	W_B $*10^3$ (mm^3)
ESN 32	80	2.4	1.5	6.3	54.7	29.5	50.3	12.8
	100	2.4	1.9	7.8	104.2	36.6	78.5	19.7
	125	2.4	2.4	9.7	199.6	45.4	122.7	30.5
	150	2.4	2.8	11.6	340.3	54.2	176.7	43.7
	200	3.3	4.9	21.2	1105.3	72.2	314.2	106.5
	250	4.1	7.3	32.9	2673.5	90.2	490.9	206.3
	300	4.9	10.1	47.1	5509.4	108.2	706.9	354.5

Table II-d. Linear mass of the pipe content G_V (kg/m)

ID (mm)	Density of fluid S_V (kg/m³)						
	800	1000	1200	1400	1600	1800	2000
25	0.4	0.5	0.6	0.7	0.8	0.9	1.0
40	1.0	1.3	1.5	1.8	2.0	2.3	2.5
50	1.6	2.0	2.4	2.7	3.1	3.5	3.9
65	2.7	3.3	4.0	4.6	5.3	6.0	6.6
80	4.0	5.0	6.0	7.0	8.0	9.0	10.1
100	6.3	7.9	9.4	11.0	12.6	14.1	15.7
125	9.8	12.3	14.7	17.2	19.6	22.1	24.5
150	14.1	17.7	21.2	24.7	28.3	31.8	35.3
200	25.1	31.4	37.7	44.0	50.3	56.5	62.8
250	39.3	49.1	58.9	68.7	78.5	88.4	98.2
300	56.5	70.7	84.8	99.0	113.1	127.2	141.4
350	77.0	96.2	115.5	134.7	153.9	173.2	192.4
400	100.5	125.7	150.8	175.9	201.1	226.2	251.3
450	127.2	159.0	190.9	222.7	254.5	286.3	318.1
500	157.1	196.3	235.6	274.9	314.2	353.4	392.7
600	226.2	282.7	339.3	395.8	452.4	508.9	565.5
700	307.9	384.8	461.8	538.8	615.8	692.7	769.7
750	353.4	441.8	530.1	618.5	706.9	795.2	883.6
800	402.1	502.7	603.2	703.7	804.2	904.8	1005.3
900	508.9	636.2	763.4	890.6	1017.9	1145.1	1272.3
1000	628.3	785.4	942.5	1099.6	1256.6	1413.7	1570.8
1200	904.8	1131.0	1357.2	1583.4	1809.6	2035.8	2261.9
1400	1231.5	1539.4	1847.3	2155.1	2463.0	2770.9	3078.8

II.5.2. Fittings

The minimum reinforced wall thickness (TE) for fittings is also calculated with the use of the ISO-equation (see Eq. II.1.). However, the allowable hoop stress (SH) is related to the fitting type.
For fittings ♪ the following allowable hoop stress is used:
- Elbow/Coupler SH= 40 N/mm^2
- Tee/Lateral/Reducer SH= 32 N/mm^2.

Table II-e. Available standard Wavistrong systems

Pressure Class (bar)	Inner Diameter (mm)														
	25-40	50	65	80	100	125	150	200	250-300	350-400	450-600	700-800	900-1000	1200	1400
8										1 3	1 2 3	3	3	3	3
10											4	4	4	4	4
12.5									1 3	1 2 3	2 3	3	3	3	
16								1 3	1 2 3	1 2 3 4	2 3 4	3 4			
20							1 2 3	1 2 3 4	1 2 3 4	1 2 3 4	2 3 4	3			
25					1 2 3	1 3	1 2 3	1 2 3 4	1 2 3 4	1 2 3 4	2 3 4				
32	1	1 3	1 3	1 2 3 4	1 2 3 4	1 3 4	1 2 3 4	1 2 3 4	1 2 3 4	2	2 2 2				
40		2		2			2	2	2	2					
50	2	2		2			2	2	2	2					

Note:
1 CJ Conical/Cylindrical adhesive bonded Joint.
2 TJ Taper/Taper adhesive bonded Joint.
3 RSLJ Rubber Seal Lock Joint.
4 RSJ Rubber Seal Joint.
(5) LJ Laminate Joint. Available for all Inner Diameter/Pressure Class combinations.
(6) FJ Flange Joint. Available for all Inner Diameter/Pressure Class combinations.

[grey box] = See higher pressure class.

Mechanical coupler (MC) is available on request.
Other joining systems are available on request.

♪ Fittings are only available in the series EST, EWT and CST. A non-tensile resistant pipe system is assembled by combining non-tensile resistant pipes and tensile resistant fittings.

II.5.3. Combined stresses

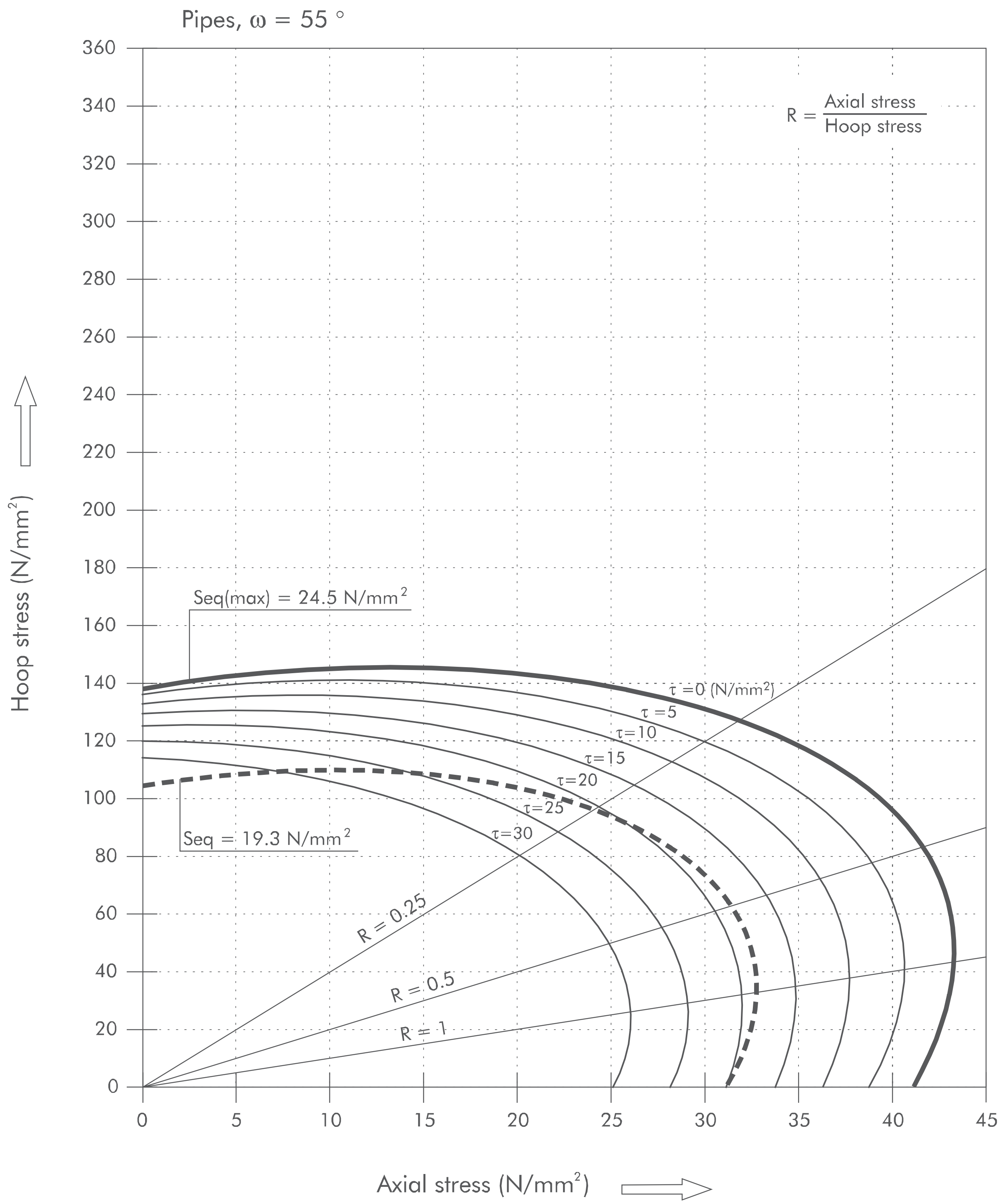
Fig. II.7-a. through II.7-c. give the allowable axial (longitudinal) and hoop (circumferential) stress, in combination with shear stress (τ), for pipes which are helical reinforced with winding angles respectively of 55°, 63° or 73°.

The equivalent stress (S_{eq}), is calculated with the Continuum Theory (see section I.) at bi-axial Hydrostatic Design Stress (HDS) level of the pipe and the use of a service (design) factor (S_f)= 0.5.
For this load situation Seq= 19.3 N/mm^2.

The maximum equivalent stress for combined stresses in the pipe wall, due to a hydrostatic load plus an external mechanical load $S_{eq\ (max)}$= 24.5 N/mm^2.

For combined stress situations the maximum service (design) factor (S_f)= 0.67.

Fig. II.7-a. Pipes, winding angle ω= 55 °

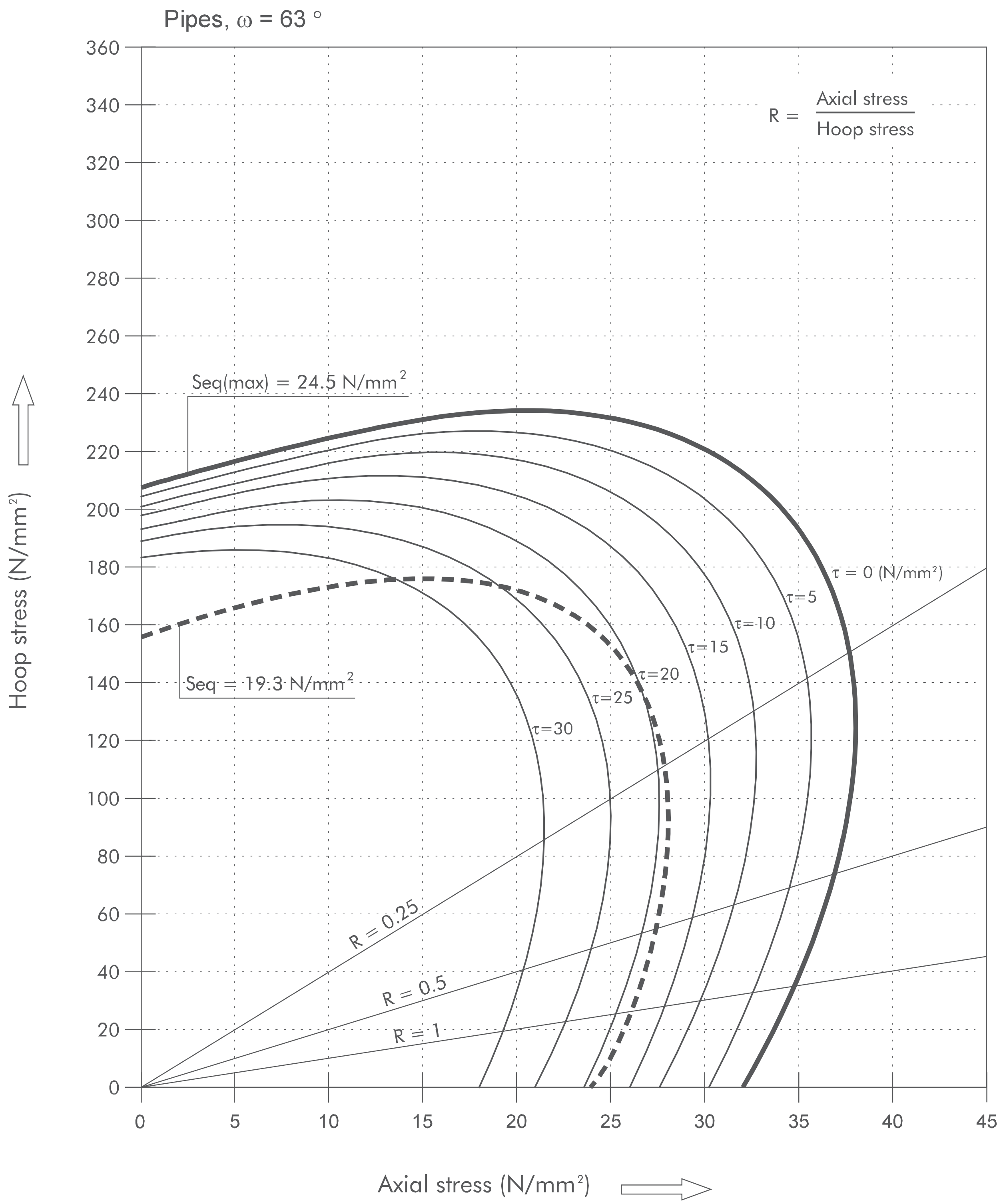


- - - Allowable stresses for hydrostatic loading; service (design) factor S_f= 0.5, S_{eq}= 19.3 N/mm².

━━ Allowable stresses for combined loading; service (design) factor S_f= 0.67, S_{eq} (max)= 24.5 N/mm².

── Allowable stresses for combined loading in combination with shear stress (τ), S_{eq} (max)= 24.5 N/mm².

Fig. II.7-b. Pipes, winding angle ω= 63 °

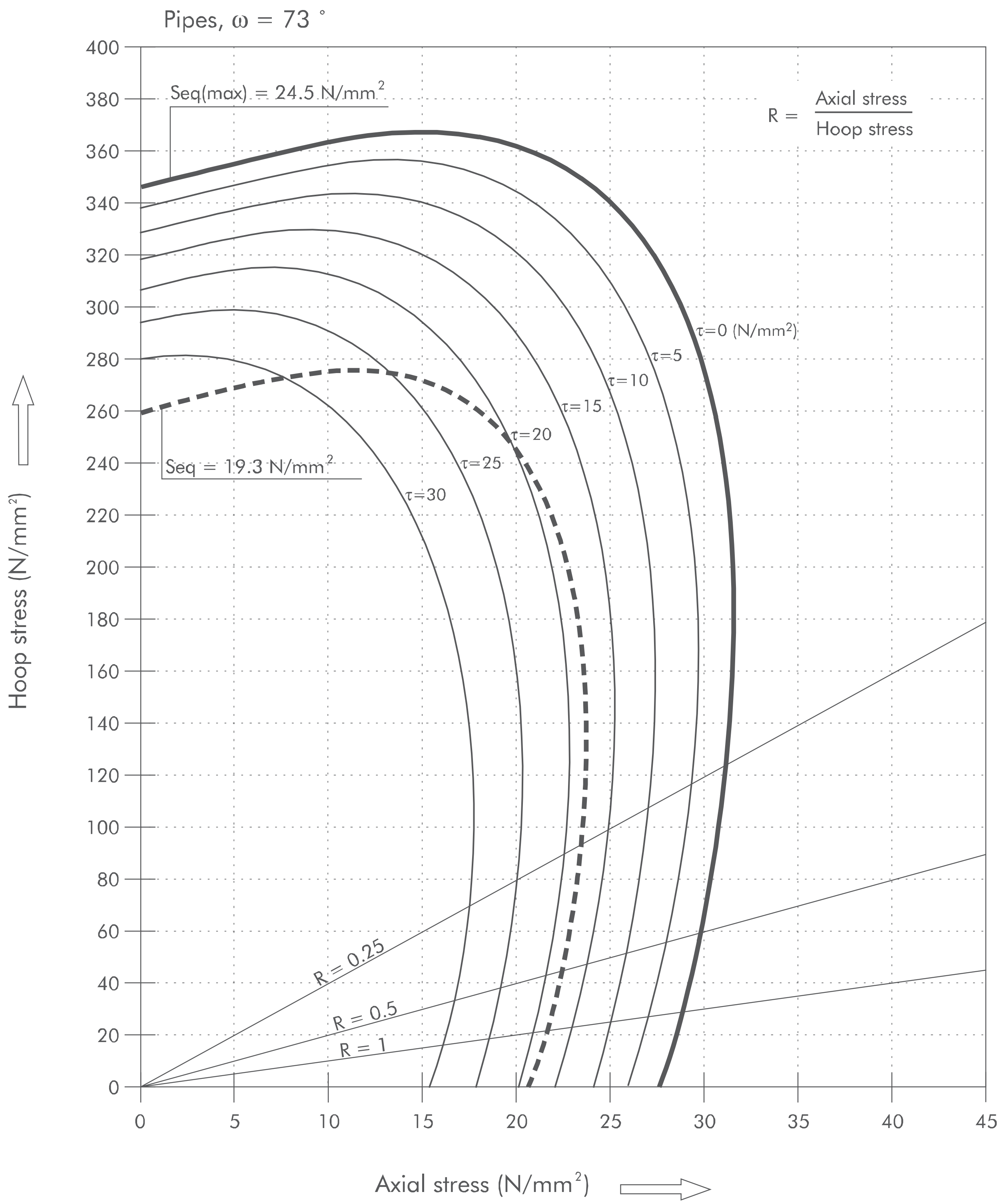


- - - Allowable stresses for hydrostatic loading; service (design) factor S_f= 0.5, S_{eq}= 19.3 N/mm².

▬ Allowable stresses for combined loading; service (design) factor S_f= 0.67, S_{eq} (max)= 24.5 N/mm².

— Allowable stresses for combined loading in combination with shear stress (τ), S_{eq} (max)= 24.5 N/mm².

Fig. II.7-c. Pipes, winding angle ω= 73 °



- - - Allowable stresses for hydrostatic loading; service (design) factor S_f= 0.5, S_{eq}= 19.3 N/mm².

▬ Allowable stresses for combined loading; service (design) factor S_f= 0.67, S_{eq} (max)= 24.5 N/mm².

— Allowable stresses for combined loading in combination with shear stress (τ), S_{eq} (max)= 24.5 N/mm².

II.6. Wavistrong pipe properties

Tables II-f. through II-j. detail the typical properties, obtained when testing Wavistrong in accordance with the mentioned test methods.

Unless otherwise stated, all properties refer to the reinforced wall and are valid for a temperature of 21 °C. For higher temperatures the temperature correction factors for the E-modules of table II-h. shall be applied.

Table II-f. Hydrostatic properties

Property	Test method	Winding angle (ω)			Unit
		55 °	63 °	73 °	
Bi-axial loading: (R= 0.50)					
Ultimate hoop stress (Weeping)	ASTM D1599	250	200		N/mm²
Ultimate Elastic Wall Stress (UEWS)	Future Pipe Industries	160	140		N/mm²
Hydrostatic Design Basis HDB (50 years)	ASTM D2992 B	150	100		N/mm²
"Hydrostatic Design Stress HDS (50 years)"	ASTM D2992 A ASTM D2992 B	50 63	 50		 N/mm²
Uni-axial loading: (R= 0.25)					
Ultimate hoop stress (Weeping)	ASTM D1599		450	370	N/mm²
Hydrostatic Design Basis HDB (50 years)	ASTM D2992 B		200	160	N/mm²
Hydrostatic Design Stress HDS (50 years)	ASTM D2992 B		100	80	N/mm²

Note: HDS= HDB * Sf

Where:
HDS = Hydrostatic Design Stress
HDB = Hydrostatic Design Basis
Sf = Service (design) factor
Sf = Maximal 0.5.

Table II-g. Mechanical properties

Property	Symbol	Test method	Winding angle (ω)			Unit
			55 °	63 °	73 °	
Axial tensile strength	S_{AT}	ASTM D2105	65	55	40	N/mm²
Axial tensile modulus ♪	E_{AT}	ASTM D2105	10,500	10,000	10,000	N/mm²
Hoop tensile strength	S_{HT}	ASTM D2290	210	260	400	N/mm²
Hoop tensile modulus	E_{HT}	ASTM D2290	20,500	27,500	37,000	N/mm²
Shear modulus	E_s		10,500	9,500	7,000	N/mm²
Volumetric modulus ♪♪	E_v		20,881	23,400	25,735	N/mm²
Axial bending strength	S_{AB}		80	65	50	N/mm²
Axial bending modulus	E_{AB}	ASTM D2925	10,500	10,000	10,000	N/mm²
Hoop Flexural/bending strength	S_{HF}	ASTM D2925	90	120	160	N/mm²
Hoop Flexural/bending modulus	E_{HF}	ASTM D2412	20,500	27,500	37,000	N/mm²
Poisson ratio Axial/Hoop♪♪♪	$v_{a,h}$	ASTM D638/E132	0.65	0.62	0.47	-
Poisson ratio Hoop/Axial♪♪♪	$v_{h,a}$	ASTM D638/E132	0.33	0.26	0.15	-

Table II-h. Temperature correction factor for modulus of elasticity RE (-)

Correction factor RE (-)		Winding angle (ω)	Temperature (°C)						
RE-Axial	RE-Hoop		20	40	60	80	100	110	121
RE1		55 °	1	0.93	0.87	0.80	0.72	0.68	0.636
RE2		63 °	1	0.93	0.87	0.80	0.72	0.68	0.636
RE3		73 °	1	0.93	0.87	0.80	0.72	0.68	0.636
	RE4	55 °	1	0.95	0.90	0.83	0.75	0.70	0.645
	RE5	63 °	1	0.97	0.94	0.90	0.85	0.82	0.737
	RE6	73 °	1	0.99	0.98	0.97	0.95	0.94	0.929

Table II-j. Physical properties

Property	Symbol	Test method	Unit	
Coefficient of linear thermal expansion	α	ASTM D 696	$2 * 10^{-6}$	mm/mm.°C
Thermal conductivity	K		0.29	W/m.°C
Specific heat	c		921	J/kg.K
Glass content (by mass)		ASTM D 2584	70 ± 5	%
Glass content (by volume)		ASTM D 2584	52 ± 7	%
Laminate Density	ρ		1850	kg/m³
Barcol hardness		ASTM D 2583	35	-
Surface resistance (Series C..)		ASTM D 257	$< 10 * 10^6$	Ω/m
Calorific value			10.5	MJ/kg
Self Ignition Temperature			256	°C
Hazen Williams	C		150.0	-
Manning Roughness Coefficient	n		0.01	-
Darcy-Weisbach Friction Factor	f		0.0	-
Surface Roughness Parameter	e		0.05	mm

♪ Axial Tensile Modulus: This modulus is commonly used as elastic modulus (E-modulus) in stress analysis.
♪♪ Volumetric Modulus: The volumetric modulus is used for hydraulic studies or surge analysis.
♪♪♪ The first index gives the direction of the contraction, the second index gives the load direction.

II.7. Head loss in pipes and fittings

II.7.1. Wavistrong pipes

Wavistrong pipeline systems have a relatively low head loss due to the smooth inner surface of the products. The head losses have been determined by using the Darcy-Weisbach formula.

The friction coefficients for the pipeline system are determined by the Colebrook-White method using a wall roughness k= 0.05 mm, including head loss over the joints.

This approximates a Hazen-Williams coefficient of 150.

For the pipes and fittings as such the wall roughness k= 0.01 to 0.02 mm.

Head loss flow charts for pipes are shown in fig. II.8. and II.9. These figures give the head loss in the pipeline system in metre head of water per metre pipe length for water at 10 °C. At higher operating temperatures the kinematical viscosity of water decreases, resulting in lower head losses.

II.7.2. Wavistrong fittings

The head loss in fittings can be calculated from the following formula:

$$\Delta H_{fitting} = \zeta \times \frac{1}{2} \times S_V \times v^2$$

(Eq. II.9.)

Where:

$\Delta H_{fitting}$ = Head loss in the fitting (N/m^2)
ζ = Friction coefficient (-)
S_V = Density of fluid (kg/m^3)
v = Flow velocity (m/s)

The friction coefficient (ζ) for elbows and tees is referred to in tables II-k. and II-l. The head loss in fittings can be expressed in an equivalent pipe length (LEQ) when using the head loss in pipes from fig. II.8. and II.9.

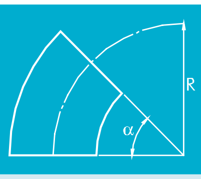
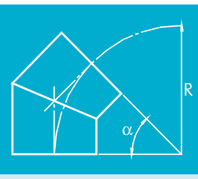
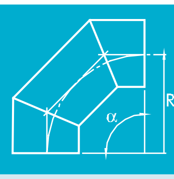
$$L_{EQ} = \frac{\Delta H_{fitting}}{\Delta H_{pipe} \times g \times 1000}$$

(Eq. II.10.)

Where:

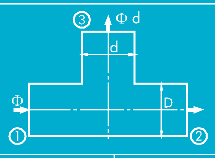
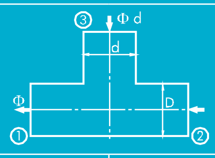
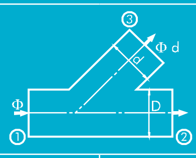
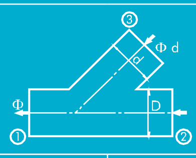
L_{EQ} = Equivalent pipe length (m)
$\Delta H_{fitting}$ = Head loss in the fitting (N/m^2)
ΔH_{pipe} = Head loss in the pipe (see fig. II.8. and II.9.) (m.h.w./m)
g = Acceleration due to gravity (m/s^2)

Table II-k. Friction coefficient ζ (-) for elbows

α			
22.5 °		0.07	
45 °	0.11	0.24	
90 °	0.16		0.30

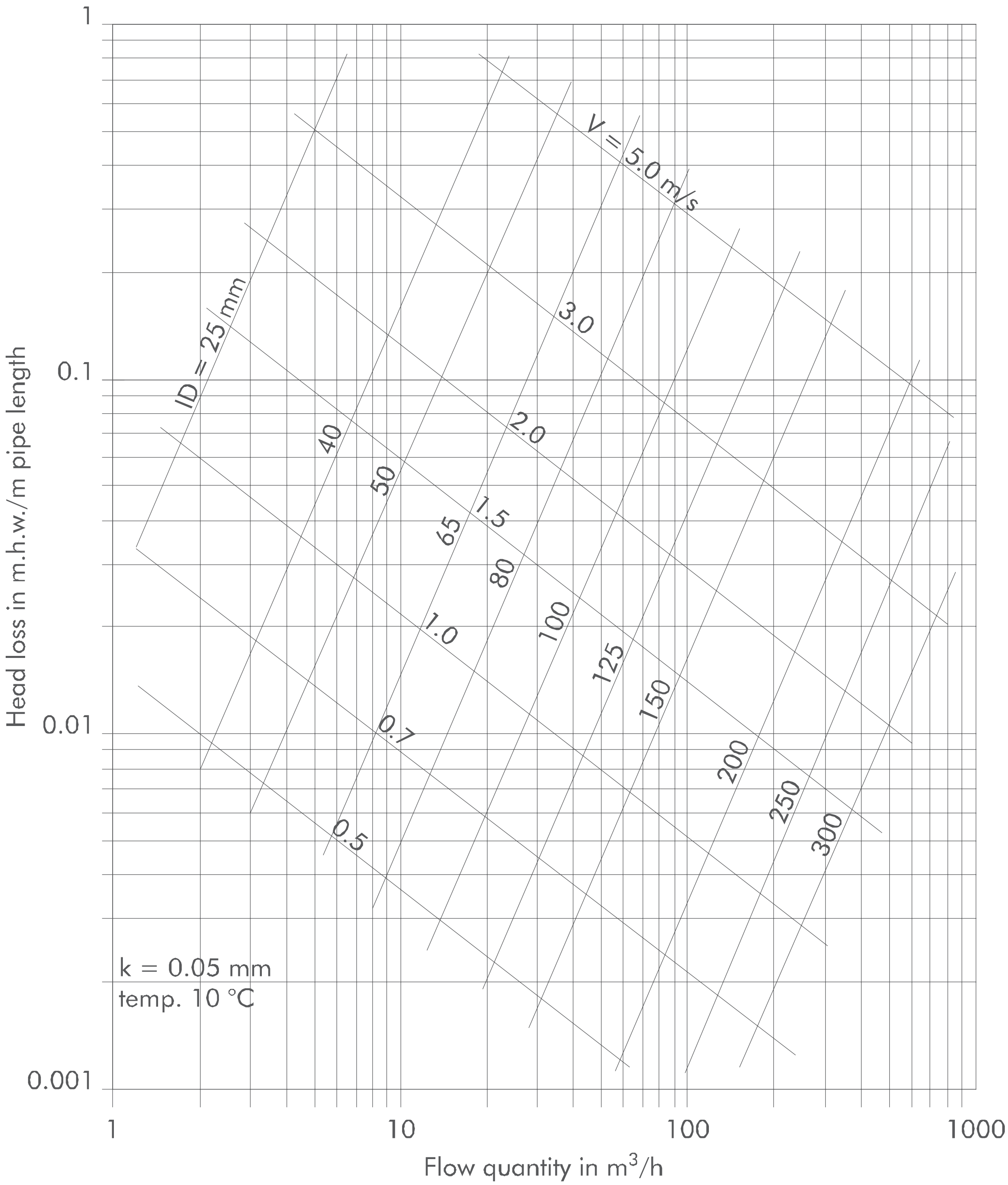
Note: Elbows ID ≥ 450 mm are mitred elbows.
For all standard elbows the radius R= 1.5 * ID.

Table II-l. Friction coefficient ζ (-) for tees and laterals

		Flow separation		Flow combination		Flow separation		Flow combination	
									
Φd / Φ	d / D	ζ	ζD	ζ	ζD	ζ	ζD	ζ	ζD
0	1	0.04	0.95	0.04	-1.20	0.04	0.90	0.04	-0,92
	0.58	0.25	1.30	0.20	-0.70	0	1.00	0	-1.00
	0.35	0	1	0	-1.00	0	2.00	0	-1.00
0.2	1	-0.08	0.88	0.17	-0.40	-0.06	0.68	0.17	-0.38
	0.58	-0.20	1.55	0.45	0.20	-0.15	0.45	0.10	-0.10
	0.35	0	3.00	0	2.00	-0.10	2.00	0	2.00
0.4	1	-0.05	0.89	0.30	0.08	-0.04	0.50	0.19	0
	0.58	-0.10	2.40	0.75	1.30	0	0.60	-0.15	0.75
	0.35	0	9.00	0	12.00	0	6.00	-1.10	9.00
0.6	1	0.07	0.95	0.41	0.47	0.07	0.38	0.09	0.22
	0.58	0	4.25	1.00	2.80	0.15	1.30	-0.60	2.15
	0.35	0	19.00	0	29.00	0.10	14.00	-2.90	20.00
0.8	1	0.21	1.10	0.51	0.72	0.20	0.35	-0.17	0.37
	0.58	0.25	7.10	1.25	4.80	0.25	2.80	-1.50	3.75
	0.35	0	33.00	0		0.20	27.00	-5.70	35.00
1	1	0.35	1.28	0.60	0.91	0.33	0.48	-0.54	0.37
	0.58	0.30		1.50	7.25	0.35	4.90	-2.90	5.40
	0.35	0		0		0.40	44.00	-9.60	54.00

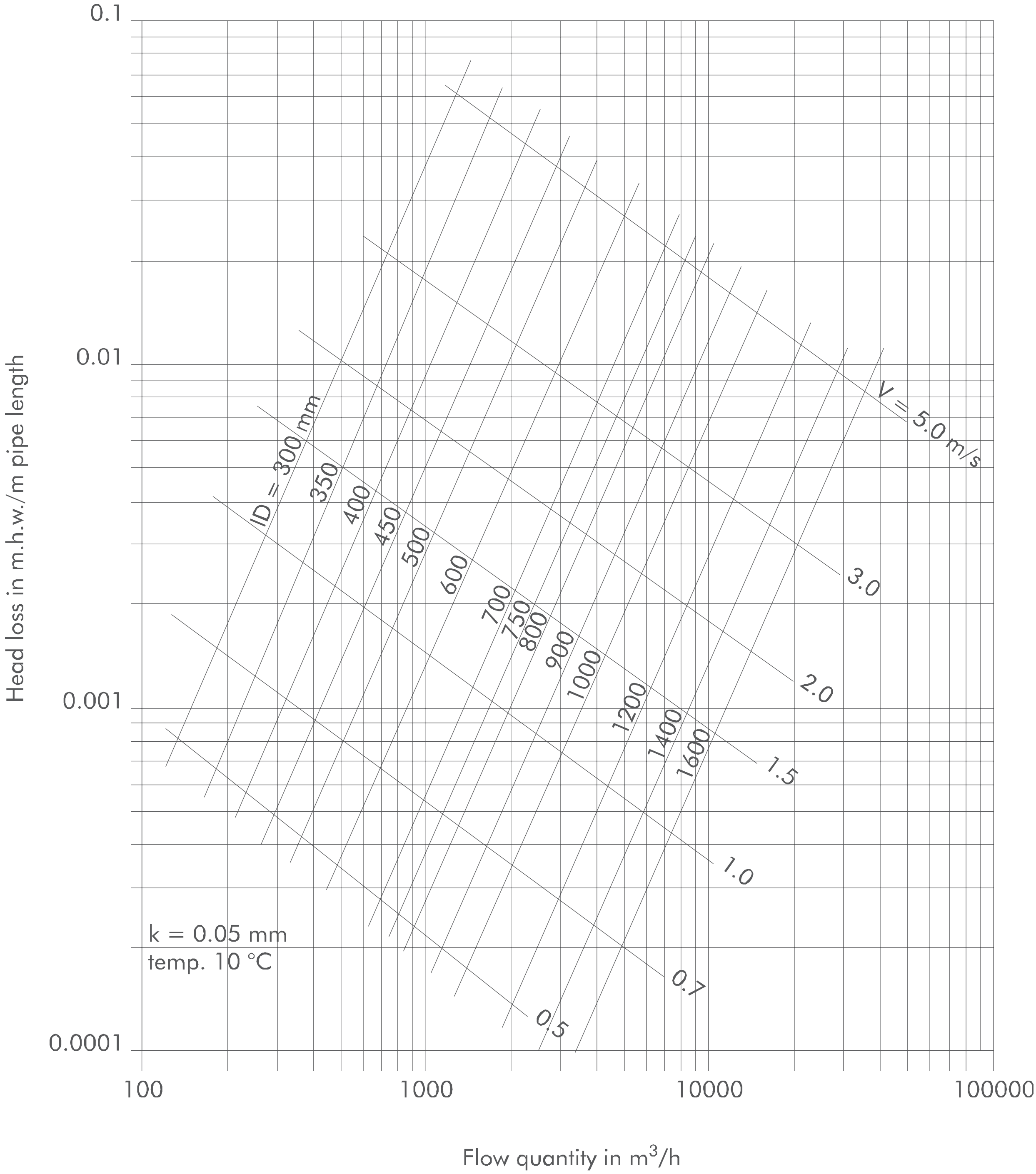
ζ = friction coefficient for pressure loss of ② relative to ①
ζd (flow separation) = friction coefficient for pressure loss of ③ relative to ①
ζd (flow combination) = friction coefficient for pressure loss of ① relative to ③
Φ = flow in the run.
Φd = flow in the branch

Fig. II.8. Head loss flow chart ID 25 mm through 300m



Velocity - According to ISO 14692, it is recommended to maintain a constant linear velocity between 1 m/s and 5 m/s when dealing with liquids, with intermittent excursions of up to 10 m/s. FPI also suggests the same continuous velocity for ideal liquids (a clean flow without corrosive and abrasive particles), with intermittent excursions of up to 10 m/s for short periods. To prevent sedimentation of the fluid, it is recommended to maintain a minimum velocity of 0.6 m/s.

Fig. II.9. Head loss flow chart ID 300 mm through 1400 mm



II.8. Bending radius

The minimum allowable bending radius (R_b) for a pipe, installed at 21 °C, is given in tables II-n. and II-o. The allowable radius depends on the operating temperature (T) and – pressure (P). For elevated operating temperatures, the indicated values of tables II-n. and II-o. have to be corrected with the temperature correction factor (R_E) from the table II-h.

The minimum allowable bending radius (R_b) is calculated with the following formula:

$$R_b = \frac{0.0005 \times R_E \times E_X \times DI}{S_A}$$

(Eq. II.11.)

Where:
R_b = Bending radius (m)
R_E = Temperature correction factor for E-modulus (see table II-h.) (-)
E_X = Axial bending modulus (see table II-g.) (N/mm²)
DI = Structural inner diameter (see section II.5.1.C.) (mm)
S_A = Remaining axial stress (N/mm²)

The value of SA is defined as follows:

$$S_A = S_{XT} - S_X$$

(Eq. II.12.)

Where:
S_A = Remaining axial stress (N/mm²)
S_{XT} = Allowable axial stress (N/mm²)
S_X = Actual axial stress due to internal pressure (N/mm²)

For bi-axial loaded systems:

$$S_X = \frac{P}{4} \times \left(\frac{ID}{T_E} + 1\right)$$

(Eq. II.13.)

For uni-axial loaded systems:

$$S_X = \frac{P}{8} \times \left(\frac{ID}{T_E} + 1\right)$$

(Eq. II.14.)

Where:
S_X = Actual axial stress due to internal pressure (N/mm²)
P = Operating pressure (MPa)
ID = Inner diameter (mm)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (mm)

The allowable axial stress (S_{XT}) depends on the type of loading (R) and the winding angle (ω) and is given in table II-m

Table II-m. Allowable axial stress SXT (N/mm^2)

R (-)	Winding angle (ω)		
	55 °	63 °	73 °
0.25	-	32	25
0.50	40	32	-

$$R = \frac{\text{axial stress}}{\text{hoop stress}}$$

The values referred to in tables II-n. and II-o. are only valid for pipes of the indicated series.
For available standard pipe systems, see table II-e.

Table II-n-1. Bending radius R_b (m) at 21 °C for series EST

Series	ID (mm)	Operating pressure (P)					
		$1 * P_N$	$0.8 * P_N$	$0.6 * P_N$	$0.4 * P_N$	$0.2 * P_N$	$0 * P_N$
EST 8	350	258	148	104	80	65	55
	400	295	169	119	91	74	63
	450	332	190	134	103	84	70
	500	368	212	148	114	93	78
	600	442	254	178	137	111	94
	700	515	296	208	160	130	110
	750	552	317	222	171	139	117
	800	557	330	234	181	148	125
	900	631	372	264	204	167	141
	1000	704	414	293	227	185	156
	1200	851	498	353	273	222	188
	1400	998	583	412	318	259	219
EST 12.5	250	156	89	63	48	39	33
	300	187	107	75	58	47	40
	350	218	125	87	67	55	46
	400	250	143	100	77	62	53
	450	281	161	112	86	70	59
	500	291	173	123	95	78	66
	600	353	208	148	114	93	79
	700	415	244	173	134	109	92
	750	446	261	185	143	117	99
	800	477	279	197	153	125	105
	900	539	315	222	172	140	118
	1000	601	350	247	191	156	131
	1200	725	422	297	229	187	158
EST 16	200	139	75	51	39	31	26
	250	158	90	63	48	39	33
	300	197	110	76	58	47	40
	350	237	130	89	68	55	46
	400	256	144	101	77	63	53
	450	295	164	114	87	70	59
	500	335	184	127	97	78	66
	600	393	219	152	116	94	79
	700	452	254	176	135	109	92
	750	492	273	189	145	117	99
	800	531	293	203	155	125	105

Table II-n-2. Bending radius R_b (m) at 21 °C for series EST (continued)

Series	ID (mm)	Operating pressure (P)					
		$1 * P_N$	$0.8 * P_N$	$0.6 * P_N$	$0.4 * P_N$	$0.2 * P_N$	$0 * P_N$
EST 20	150	96	54	38	29	24	20
	200	115	69	49	38	31	26
	250	146	87	62	48	39	33
	300	178	105	74	57	47	40
	350	209	123	87	67	55	46
	400	241	140	99	77	62	53
	450	273	158	112	86	70	59
	500	305	176	124	96	78	66
	600	355	209	148	115	93	79
	700	418	245	173	134	109	92
	750	450	263	185	143	117	99
	800	482	281	198	153	125	105
EST 25	100	40	28	22	18	15	13
	125	71	43	31	24	20	17
	150	87	52	37	29	23	20
	200	119	70	49	38	31	26
	250	151	88	62	48	39	33
	300	183	106	75	58	47	40
	350	215	124	87	67	55	46
	400	237	139	99	76	62	53
	450	269	157	111	86	70	59
	500	301	175	124	96	78	66
	600	365	212	149	115	94	79
EST 32	80	34	24	18	15	12	11
	100	63	36	25	19	16	13
	125	83	46	32	24	20	17
	150	104	56	39	29	24	20
	200	135	74	51	39	31	26
	250	166	92	63	48	39	33
	300	197	110	76	58	47	40
	350	228	127	88	68	55	46
	400	259	145	101	77	63	53

Table II-n-3. Bending radius R_b (m) at 21 °C for series EST (continued)

Series	ID (mm)	Operating pressure (P)					
		1 * P_N	0.8 * P_N	0.6 * P_N	0.4 * P_N	0.2 * P_N	0 * P_N
EST 40	50	24	16	12	9	8	7
	65	29	20	15	12	10	9
	80	52	29	20	16	13	11
	100	61	35	25	19	16	13
	125	78	45	31	24	20	17
	150	88	52	37	29	23	20
	200	121	71	50	38	31	26
	250	148	87	62	48	39	33
	300	182	106	74	58	47	40
	350	209	122	87	67	55	46
	400	242	141	99	77	62	53
EST 50	25	6	5	5	4	4	3
	40	20	13	10	8	6	5
	50	30	18	13	10	8	7
	65	40	23	16	13	10	9
	80	50	29	20	16	13	11
	100	59	35	25	19	16	13
	125	76	44	31	24	20	17
	150	88	52	37	29	23	20
	200	122	71	50	38	31	26
	250	151	88	62	48	39	33
	300	181	105	74	57	47	40
	350	210	123	87	67	55	46
	400	239	140	99	76	62	53

Table II-o. Bending radius Rb (m) at 21 °C for series ESN

Series	ID (mm)	Operating pressure (P)					
		1 * P_N	0.8 * P_N	0.6 * P_N	0.4 * P_N	0.2 * P_N	0 * P_N
ESN 10	450	288	200	153	124	105	90
	500	333	227	173	139	116	100
	600	404	275	208	167	140	120
	700	454	314	240	194	163	140
	750	500	341	259	209	175	150
	800	525	361	275	222	186	160
	900	595	408	310	250	209	180
	1000	666	455	345	278	233	200
	1200	808	549	415	334	279	240
	1400	950	643	486	390	326	280
ESN 16	350	258	148	104	80	65	55
	400	295	169	119	91	74	63
	450	332	190	134	103	84	70
	500	368	212	148	114	93	78
	600	442	254	178	137	111	94
	700	515	296	208	160	130	110
	750	552	317	222	171	139	117
	800	557	330	234	181	148	125
ESN 20	200	92	66	52	43	36	31
	250	186	106	74	57	47	39
	300	223	128	89	69	56	47
	350	260	149	104	80	65	55
	400	297	170	119	92	74	63
	450	334	191	134	103	84	70
	500	346	205	146	113	93	78
	600	420	248	176	136	111	94
ESN 25	200	150	86	60	46	37	31
	250	173	103	73	57	46	39
	300	214	125	88	68	56	47
	350	257	148	104	80	65	55
	400	279	165	117	91	74	63
	450	321	188	133	102	84	70
	500	364	210	148	114	93	78
	600	428	250	177	137	111	94
ESN 32	80	22	19	17	15	14	13
	100	34	28	23	20	18	16
	125	59	42	33	27	23	20
	150	114	65	45	35	28	24
	200	137	82	58	45	37	31
	250	174	103	73	57	46	39
	300	212	125	88	68	56	47

II.9. Fluid (water) hammer

Fluid (water) hammer can be defined as the occurrence of a pressure change in a closed piping system, caused by a change in the flow velocity.

Therefore, fluid (water) hammer can occur in all kinds of piping systems used for the transport of liquids.

The greater and faster the velocity change, the greater the pressure change will be. The relation between change of velocity and pressure change can be derived from the formula of Joukowsky ♪:

$$\Delta P = \frac{c}{g} \times \Delta v$$

(Eq. II.15.)

Where:
ΔP = Pressure change (m.h.w.)
c = Wave velocity (m/s)
g = Acceleration due to gravity (m/s^2)
Δv = Change in flow velocity (m/s)

In accordance with AWWA Manual M45 a transient pressure increase of 1.4 times the design pressure is allowable; this is also valid for the Wavistrong piping system.

The wave velocity (c) depends on the type of fluid, pipe dimensions and the E-modulus. The wave velocity can be calculated with the aid of the Talbot equation:

$$c = \frac{1000}{\sqrt{S_V \times \left(\frac{1}{K_V} + \frac{ID}{T_E \times E_V} \times f\right)}}$$

(Eq. II.16.)

Where:
c = Wave velocity (m/s)
S_V = Density of the fluid (kg/m^3)
K_V = Compression modulus of the fluid (N/mm2)
ID = Inner diameter (mm)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (mm)
E_V = Volumetric E-modulus (see table II-p.) (N/mm^2)
f = Constant (see table II-q.) (-)

♪ This calculation method is only valid for straight pipeline sections with various types of joints. On request, system calculations can be made by a third party.

For isotropic materials, the volumetric E-modulus is equal to the E-modulus.

When dealing with an-isotropic (anisotropic or orthotropic) materials, like Glass Fiber Reinforced Composites (GRE/RTR), where the material characteristics rely on the winding angle (ω), the volumetric E-modulus (E_V) can be determined using the following equation:

$$E_V = \frac{3\sqrt{E_X \times E_H^2}}{1 - N_{XY} \times N_{YX}}$$

(Eq. II.17.)

Where:
E_V = Volumetric E-modulus (N/mm²)
E_X = Axial bending modulus (see table II-g.) (N/mm²)
E_H = Hoop bending modulus (see table II-g.) (N/mm²)
N_{XY} = Poisson ratio axial/hoop (see table II-g.) (-)
N_{YX} = Poisson ratio hoop/axial (see table II-g.) (-)

For the three winding angles (ω) of the Wavistrong pipes the volumetric E-modulus (EV) is given in table II-p.

Table II-p. Volumetric E-modulus E_V (N/mm²)

Winding angle (ω)	55 °	63 °	73 °
E_V	20,881	23,400	25,735

The constant (f) in the Talbot equation (Eq. II.16.) depends on the type of anchoring of the system.

A. The pipeline may be anchored up-stream; in this case the system is loaded bi-axially.
This can be achieved in a tensile resistant piping system.

$$f1 = \frac{5}{4} - 0.5 \times N_{XY} \times N_{YX}$$

(Eq. II.18.)

B. The pipeline may be anchored completely to prevent axial displacements.
This may occur in tensile resistant and non-tensile resistant piping systems.

$$f2 = 1 - N_{XY} \times N_{YX}$$

(Eq. II.19.)

C. The pipeline may be installed with expansion joints so that there will be no axial stresses.
This will happen in case of non-tensile resistant pipelines.

$$f3 = 1 - 0.5 \times N_{YX}$$

(Eq. II.20.)

For the three winding angles (ω) of the Wavistrong series EST and ESN the constants (f) are given in table II-q.

Table II-q. Constant f (-)

Constant	Winding angle (ω)		
	55 °	63 °	73 °
f1	1.1265	1.1694	-
f2	0.753	0.8388	0.9295
f3	-	0.87	0.925

The values of the wave velocity (c1 through c3) are related to the type of anchoring of the pipeline system (constant f1 through f3).

For Wavistrong series EST the wave velocities (c1 and c2) are listed in table II-r.; the wave velocities (c2 and c3) for Wavistrong series ESN are shown in table II-s.

Table II-r. Wave velocity c1 and c2 for series EST ♪

Series	ID (mm)	c1 (m/s)	c2 (m/s)
EST 8	350	385	449
	400	385	449
	450	385	449
	500	385	449
	600	385	449
	700	385	449
	750	385	449
	800	388	452
	900	388	451
	1000	388	451
	1200	387	451
	1400	387	450
EST 12.5	250	420	503
	300	420	503
	350	420	503
	400	420	503
	450	420	503
	500	424	508
	600	424	507
	700	423	507
	750	423	506
	800	423	506
	900	422	506
	1000	422	506
	1200	422	505
EST 16	200	465	554
	250	470	560
	300	468	558
	350	466	556
	400	469	559
	450	468	558
	500	467	556
	600	468	558
	700	469	558
	750	468	558
	800	467	557

Series	ID (mm)	c1 (m/s)	c2 (m/s)
EST 20	150	518	614
	200	525	622
	250	524	621
	300	523	620
	350	522	619
	400	522	618
	450	522	618
	500	521	618
	600	523	620
	700	522	619
	750	522	619
	800	522	618
EST 25	100	615	720
	125	580	682
	150	578	680
	200	576	678
	250	575	677
	300	574	676
	350	574	675
	400	576	678
	450	576	677
	500	575	677
	600	574	676
EST 32	80	672	781
	100	635	742
	125	631	738
	150	629	735
	200	630	736
	250	631	738
	300	632	738
	350	633	739
	400	633	739

♪ Values of table II-r. are valid for the following conditions:
K_v= 2050 N/mm^2.
S_v= 1000 kg/m^3.

Series	ID (mm)	c1 (m/s)	c2 (m/s)
EST 40	50	721	831
	65	728	838
	80	694	803
	100	698	807
	125	696	805
	150	700	810
	200	698	807
	250	699	809
	300	698	807
	350	699	808
	400	698	807
EST 50	25	911	1016
	40	782	892
	50	763	873
	65	760	870
	80	758	868
	100	763	873
	125	760	871
	150	763	873
	200	759	870
	250	760	871
	300	760	871
	350	761	872
	400	761	872

Table II-s. Wave velocity c2 and c3 for series ESN*

Series	ID (mm)	c2 (m/s)	c3 (m/s)
ESN 10	450	430	431
	500	426	427
	600	425	426
	700	429	429
	750	426	427
	800	428	429
	900	427	428
	1000	426	427
	1200	425	426
	1400	425	426
ESN 16	350	449	441
	400	449	441
	450	449	441
	500	449	441
	600	449	441
	700	449	441
	750	449	441
	800	452	444
ESN 20	200	536	528
	250	496	488
	300	496	488
	350	496	488
	400	496	488
	450	496	488
	500	500	492
	600	499	491
ESN 25	200	546	537
	250	551	543
	300	549	540
	350	547	539
	400	551	542
	450	549	540
	500	548	539
	600	549	540

Series	ID (mm)	c2 (m/s)	c3 (m/s)
ESN 32	80		
	100		
	125		
	150		
	200		
	250		
	300		

* Values of table II-s. are valid for the following conditions:
K_v= 2050 N/mm².
S_v= 1000 kg/m³.

II.10. Stiffness

An investigation of standards concerning the stiffness ♪ of flexible pipes shows that there are different ways to express the resistance to circumferential deflection of a pipe. The following identifications illustrate this point.

A. Specific Ring Stiffness (S)

The Specific Ring Stiffness (S) is described in EN 1228 and is calculated with the following formula:

$$S = \frac{1}{12} \times E_H \times \left(\frac{T_E}{ID + T_E}\right)^3$$

(Eq. II.21.)

Where:
S = Specific Ring Stiffness (N/m^2)
E_H = Hoop bending modulus (see table II-g.) (N/m^2)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (mm)
ID = Inner diameter (mm)

Note: The Specific Ring Stiffness (S) used to be Specific Tangential Initial Stiffness =STIS.

B. Pipe Stiffness (PS)

The Pipe Stiffness (PS) is described in ASTM D 2412 and can be calculated as follows:

$$PS = 4.474 \times E_H \times \left(\frac{T_E}{ID + T_E}\right)^3$$

(Eq. II.22.)

Where:
PS = Pipe Stiffness (psi)
E_H = Hoop bending modulus (see table II-g.) (psi)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (in)
ID = Inner diameter (in)

The Pipe Stiffness (PS) can also be calculated from the S-value by the following equation:

$$PS = 0.007787 \times S$$

(Eq. II.23.)

Where:
PS = Pipe Stiffness (psi)
S = Specific Ring Stiffness (see Eq. II.21.) (N/m^2)

♪ The stiffness identifications described in this section of the Engineering Guide represent the initial resistance to circumferential deflection of the pipe. To determine the long term stiffness the initial hoop bending modulus shall be decreased by a multiplication factor (α), representing the reduction of the modulus due to (i) the design life time of the pipe (ageing) and (ii) the operating environment of the pipe (wet)

C. Stiffness Factor (SF)

Another identification of the stiffness is called the Stiffness Factor (SF) and is also described in ASTM D 2412.

$$SF = \frac{1}{12} \times E_H \times T_E^3$$

(Eq. II.24.)

Where:
SF = Stiffness Factor (in^2.lb/in)
E_H = Hoop bending modulus (see table II-g.) (psi)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (in)

The Stiffness Factor (SF) can also be calculated from the S-value by using the following formula:

$$SF = 8.848 \times (ID+T_E)^3 \times S$$

(Eq. II.25.)

Where:
SF = Stiffness Factor (in^2.lb/in)
ID = Inner diameter (m)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (m)
S = Specific Ring Stiffness (see Eq. II.21.) (N/m^2)

There is also a relation between the Stiffness Factor (SF) and the Pipe Stiffness (PS):

$$SF = 0.149 \times r^3_m \times PS$$

(Eq. II.26.)

Where:
SF = Stiffness Factor (in^2.lb/in)
r_m = Mean pipe radius (in)
PS = Pipe Stiffness (see Eq. II.22.). (psi)

Note: $rm = 0.5 * (ID + 2 * T_L + T_E)$

Tables II-t. and II-u. show the values of the stiffness of the standard Wavistrong pipes according to various stiffness identifications at 21 °C.

For the determination of stiffness at elevated temperature the temperature correction factor for the hoop bending modulus of elasticity (RE) shall be applied (see table II-h.).

Table II-t. Stiffness for series EST at 21 °C

Series EST				
Series	ID (mm)	S (N/m²)	PS (psi)	SF (in²lb/in)
EST 8	350	1150	9	450
	400	1150	9	650
	450	1150	9	950
	500	1150	9	1300
	600	1150	9	2250
	700	1150	9	3550
	750	1150	9	4400
	800	1200	9	5550
	900	1200	9	7900
	1000	1200	9	10800
	1200	1200	9	18500
	1400	1200	9	29250
EST 12.5	250	1650	13	250
	300	1650	13	400
	350	1650	13	650
	400	1660	13	950
	450	1650	13	1400
	500	1750	14	2000
	600	1750	14	3450
	700	1750	13	5400
	750	1700	13	6650
	800	1700	13	8050
	900	1700	13	11400
	1000	1700	13	15600
	1200	1700	13	26800
EST 16	200	3200	25	250
	250	3450	27	500
	300	3350	26	850
	350	3250	25	1300
	400	3400	27	2000
	450	3350	26	2800
	500	3300	26	3800
	600	3350	26	6650
	700	3400	26	10650
	750	3350	26	13000
	800	3300	26	15600

Series EST				
Series	ID (mm)	S (N/m²)	PS (psi)	SF (in².lb/in)
EST 20	150	6650	52	200
	200	7300	57	550
	250	7200	56	1050
	300	7100	55	1800
	350	7050	55	2800
	400	7000	54	4150
	450	6950	54	5900
	500	6900	54	8050
	600	7100	55	14200
	700	7050	55	22400
	750	7000	55	27400
	800	7000	54	33200
EST25	100	22000	170	210
	125	14500	110	270
	150	14200	110	450
	200	13800	110	1050
	250	13700	105	2000
	300	13500	105	3450
	350	13400	105	5400
	400	13800	110	8350
	450	13700	105	11800
	500	13700	105	16000
	600	13500	105	27500
EST 32	80	42200	330	200
	100	27800	220	250
	125	26500	210	500
	150	25800	200	850
	200	26300	200	2000
	250	26600	210	4000
	300	26800	210	6900
	350	27000	210	11000
	400	27000	210	16500

Series EST				
Series	ID (mm)	S (N/m^2)	PS (psi)	SF (in^2.lb/in)
EST 40	50	71700	560	90
	65	77100	600	210
	80	53300	400	250
	100	55700	450	550
	125	54700	450	1050
	150	57300	450	1900
	200	55700	450	4350
	250	56700	450	8650
	300	55700	450	14650
	350	56400	450	23600
	400	55700	450	34800
EST 50	25	520000	4000	90
	40	136000	1100	90
	50	112000	850	140
	65	108500	850	300
	80	106000	827	550
	100	112000	850	1100
	125	109000	850	2150
	150	112000	850	3800
	200	108000	850	8650
	250	109000	850	17000
	300	109000	850	29500
	350	110000	850	47000
	400	110000	850	70400

Table II-u. Stiffness for series ESN at 21 °C

Series ESN				
Series	ID (mm)	S (N/m²)	PS (psi)	SF (in².lb/in)
ESN 10	450	1200	9	1000
	500	1150	9	1250
	600	1100	9	2150
	700	1150	9	3600
	750	1150	9	4300
	800	1150	9	5300
	900	1150	9	7500
	1000	1150	9	10200
	1200	1100	9	17400
	1400	1100	9	27300
ESN 16	350	1150	9	450
	400	1150	9	650
	450	1150	9	950
	500	1150	9	1300
	600	1150	9	2250
	700	1150	9	3550
	750	1150	9	4400
	800	1200	9	5550
ESN 20	200	3800	30	300
	250	2200	17	350
	300	2200	17	550
	350	2200	17	850
	400	2200	17	1300
	450	2200	17	1850
	500	2350	18	2700
	600	2350	18	4600
ESN 25	200	4300	34	300
	250	4650	36	650
	300	4500	35	1100
	350	4400	34	1750
	400	4550	36	2700
	450	4500	35	3750
	500	4400	34	5050
	600	4500	35	8900

Series EST				
Series	ID (mm)	S (N/m²)	PS (psi)	SF (in².lb/in)
ESN 32	80	56500	450	300
	100	29500	250	300
	125	15500	120	300
	150	8950	70	300
	200	9800	76	750
	250	9650	75	1400
	300	9500	74	2400

II.11. Buckling pressure

For the calculation of the buckling pressure (P_B) ♪ for Wavistrong pipes, the formula for thin wall pipes (mean radius/wall thickness > 10) shall be used.

The ultimate buckling pressure for pipes in the series EST and ESN is listed in tables II-v. and II-w.

The tabled values are valid for an operating temperature (T) of 21 °C and are calculated in accordance with equation Eq. II.27. ♫ (pipe without stiff ends) using a safety factor Sb= 1.

The allowable buckling pressure depends on the stability of the product as well as the type of pipe installation and service conditions. The transition from a stable into an unstable condition will take place abruptly. Therefore, an adequate safety factor (Sb) has to be taken into account.

Depending on the pipe installation and service conditions a safety factor Sb > 1 is normally chosen.

When underground pipes are properly backfilled the buckling pressure resistance is affected positively by the support of the surrounding soil. Our engineers may be contacted for advice.

Some extra buckling pressure allowance can be created by the application of stiff pipe ends or stiffening rings.

In case of integral joints, the pipe ends are typically much stiffer than the pipe body itself and can therefore contribute to the ultimate buckling pressure.

♪ Buckling pressure (P_B)= External Pressure (P_E) – Internal Pressure (PI).
Full vacuum means: $P_E - P_I$= 1 bar.
♫ Roark/Young, Formulas for stress and strain, McGraw-Hill, fifth edition.

Buckling Pressure (P_B), pipe without stiff ends:

$$P_B = \frac{S_F}{S_B} \times 2.5 \times \frac{E_H}{1-N_{XY} \times N_{YX}} \times \left(\frac{T_E}{r_m}\right)^3$$

(Eq. II.27.)

Where:

P_B = Buckling pressure (bar)
S_F = Service factor (SF= 0.75) (-)
S_b = Load dependent safety factor (-)
E_H = Hoop bending modulus (see table II-g.) (N/mm^2)
N_{XY} = Poisson ratio axial/hoop (see table II-g.) (-)
N_{YX} = Poisson ratio hoop/axial (see table II-g.) (-)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (mm)
r_m = Mean pipe radius (mm)

Note: rm = 0.5 * (ID + 2 * T_L + T_E)

For the determination of buckling pressure at temperatures exceeding 21 °C the temperature correction factors for the hoop bending modulus of elasticity (RE) shall be applied (see table II-h.). Buckling pressure at elevated temperature (PBT) is calculated with the aid of Eq. II.28.

$$P_{BT}=P_B \times R_E$$

(Eq. II.28.)

Where:

P_{BT} = Buckling pressure at elevated temperature (bar)
P_B = Buckling pressure at 21 °C (see tables II-v. and II-w.) (bar)
R_E = Temperature correction factor (RE4, RE5, RE6) for E-modulus (see table II-h.) (-)

Table II-v. Ultimate buckling pressure P_B (bar) series EST at 21 °C and S_B= 1

ID (mm)	Pressure class (bar)							
	8	12.5	16	20	25	32	40	50
25								110.8
40								30.4
50							16.2	25.3
65							17.6	24.8
80						9.7	12.3	24.5
100					5.1	6.5	12.9	26.0
125					3.4	6.2	12.8	25.4
150				1.6	3.3	6.0	13.4	26.2
200			0.8	1.7	3.3	6.2	13.1	25.5
250		0.4	0.8	1.7	3.2	6.3	13.4	25.7
300		0.4	0.8	1.7	3.2	6.3	13.2	25.9
350	0.2	0.4	0.8	1.7	3.2	6.4	13.4	26.0
400	0.2	0.4	0.8	1.7	3.3	6.4	13.2	26.1
450	0.2	0.4	0.8	1.7	3.3	6.4		
500	0.2	0.4	0.8	1.6	3.2			
600	0.2	0.4	0.8	1.7	3.2			
700	0.2	0.4	0.8	1.7	3.2			
750	0.2	0.4	0.8	1.7				
800	0.3	0.4	0.8	1.7				
900	0.3	0.4						
1000	0.3	0.4						
1200	0.3	0.4						
1400	0.3							

Table II-w. Ultimate buckling pressure P_B (bar) series ESN at 21 °C and S_B= 1

ID (mm)	Pressure class (bar)				
	10	16	20	25	32
80					11.7
100					6.1
125					3.2
150					1.9
200			0.8	0.9	2.1
250			0.5	1.0	2.0
300			0.5	1.0	2.0
350		0.2	0.5	0.9	
400		0.2	0.5	1.0	
450	0.2	0.2	0.5	1.0	
500	0.2	0.2	0.5	0.9	
600	0.2	0.2	0.5	1.0	
700	0.2	0.2			
750	0.2	0.2			
800	0.2	0.3			
900	0.2				
1000	0.2				
1200	0.2				
1400	0.2				

II.12. Classification

The standard Wavistrong pipes can be classified in accordance with ASTM D2996, indicating type, grade and Hydrostatic Design Basis (HDB).

The classification for all pipes in the series EST 12.5 through EST 50 is 11FX1. Kindly review the footnote. ♪

The classification for all pipes in the series EST 8 is 11FU1.

For the Wavistrong non-tensile resistant pipes in the series ESN 16 through ESN 32 the classification code in accordance with ASTM D 2310 is 11FY2.

The classification of pipes in the series ESN 10 is 11FX2.

The complete pipe designation code in accordance with ASTM D 2996, also identifying the cell classification designations for short term rupture strength, longitudinal tensile strength, longitudinal tensile modulus (EX) and apparent Stiffness Factor (SF) is presented in table II-x.

♪ Errors may occur in categorizing cells as 11FX due to the fact that the HDB classification X is only intended for products designed with a range of HDB 138 MPa to 172 MPa. Achieving such higher HDB/LCL for elevated temperature requirements can be a challenging task.

Table II-x. Designation code

	Series												
	EST	ESN	EST	EST	ESN	EST	ESN	EST	ESN	EST	ESN	EST	EST
PN (bar)	8	10	12.5	16		20		25		32		40	50
Code	11FU1	11FX2	11FX1	11FX1	11FY2	11FX1	11FY2	11FX1	11FY2	11FX1	11FY2	11FX1	11FX1
ID													
25													-2111
40													-2111
50												-2111	-2111
65												-2112	-2112
80										-2112	-5112	-2112	-2112
100								-2112		-2112	-5112	-2112	-2113
125								-2112		-2112	-5112	-2113	-2115
150						-2112		-2112		-2112	-5112	-2114	-2116
200				-2112		-2112	-5112	-2113	-5112	-2115	-5112	-2116	-2116
250			-2112	-2112		-2113	-5112	-2115	-5112	-2116	-5113	-2116	-2116
300			-2112	-2112		-2114	-5112	-2116	-5113	-2116	-5115	-2116	-2116
350	-1112		-2112	-2113	-5112	-2116	-5112	-2116	-5114	-2116		-2116	-2116
400	-1112		-2112	-2115	-5112	-2116	-5113	-2116	-5116	-2116		-2116	-2116
450	-1112	-4012	-2113	-2116	-5112	-2116	-5114	-2116	-5116				
500	-1113	-4013	-2115	-2116	-5113	-2116	-5116	-2116	-5116				
600	-1115	-4015	-2116	-2116	-5115	-2116	-5116	-2116	-5116				
700	-1116	-4016	-2116	-2116	-5116	-2116							
750	-1116	-4016	-2116	-2116	-5116	-2116							
800	-1116	-4016	-2116	-2116	-5116	-2116							
900	-1116	-4016	-2116										
1000	-1116	-4016	-2116										
1200	-1116	-4016	-2116										
1400	-1116	-4016											

3. WAVISTRONG ABOVEGROUND PIPE SYSTEMS

III.1. Design

In nearly all aboveground applications thrust resistant types of joints are used. These can be adhesive bonded joint, rubber seal lock joint, laminated joint or flanged joint.

In case of well supported and anchored pipe lines non-thrust resistant systems can be used. These are rubber seal joint or mechanically jointed systems.

Section II.4. gives a brief review of the various types of joining systems.

III.2. Supports

Aboveground pipeline systems are installed on supports.

Pipe systems with flanged joints or rubber seal (lock) joints shall have at least one support per joint (see fig. III.1.). In situations where mechanical couplers are used, Future Pipe Industries engineers will be pleased to help and inform you with requirements of the supports.

If tensile resistant joints are used, the support distance must not exceed the values listed in tables III-c. through III-e. Be aware of the required correction of the support distance due to specific operating conditions, as mentioned in section III.5.

Whether the support system is new or old, the joints must not interfere with the supports and the supports are located next to the joint (see fig. III.1.).

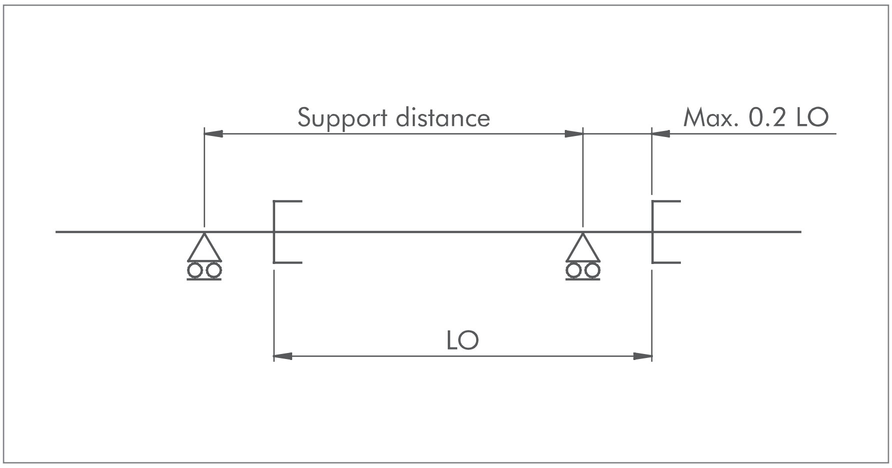


Fig. III.1. Support next to the joint

III.3. Clamps

Wavistrong pipe systems have several types of clamps that can be used. Point- and line loading must be avoided and flat strips must be used (see fig. III.2.a. and b.). The width of the clamps must be in accordance with relevant standards. The inner surface of the clamp must be provided with either a protective rubber or thermoplastic layer.

Supports enabling the pipe system to move freely in the longitudinal direction of the pipe. To determine the appropriate amount of friction for the sliding base (nominal to low), a stress analysis should be conducted. For a low friction sliding base, a PTFE pad can be recommended.

For the design of clamps, detailed drawings are available on request.

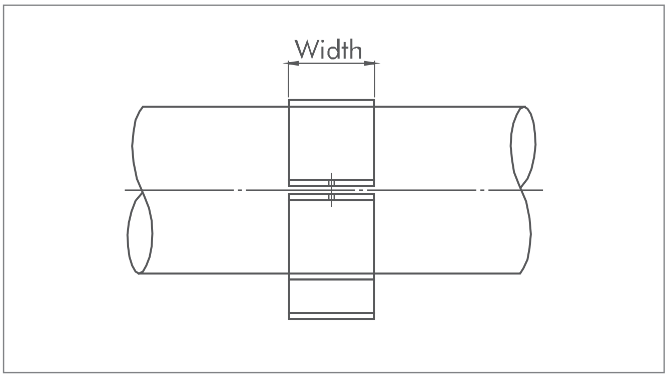


Fig. III.2.a. Single clamp

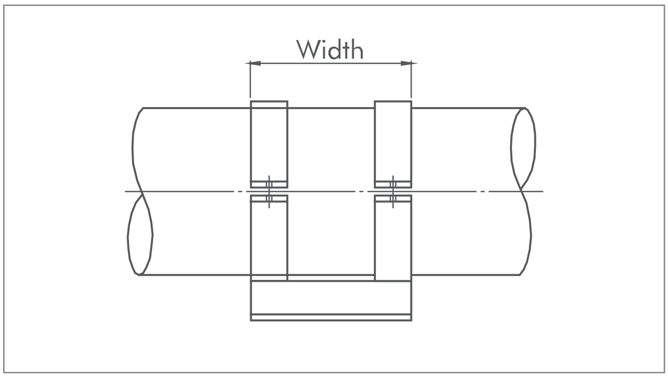


Fig. III.2.b. Double clamp

III.4. Support distance

Tables III-c. through III-e. show the maximum support distance (L') of various pipe series at various operating pressures (P) and operating temperatures (T).

Calculations are made for pipes filled with fluid having a density S_V= 1000 kg/m³.

These tables enable the selection of a pipe system for a given support distance or the determination of the maximum allowable distance between the supports for a given pipe system.

Be aware of remarks in section III.2.

The support distance is restricted by one of the following two criteria:

A. The axial stress
The support distance is related to the internal pressure in the pipe.

B. The allowable sag
For aboveground piping systems, vertical deflections shall not exceed 12.5 mm or 0.5 % of span length or support spacing, whichever is smaller.

The span length is divided into:
- Single span length (L_S) as described in section III.4.1.
- Continuous span length (L_C) as described in section III.4.2.

III.4.1. Single span length

The single span length (L_S) is the length between two supports of one single pipe or a string of flexible jointed pipes (see fig. III.3.).

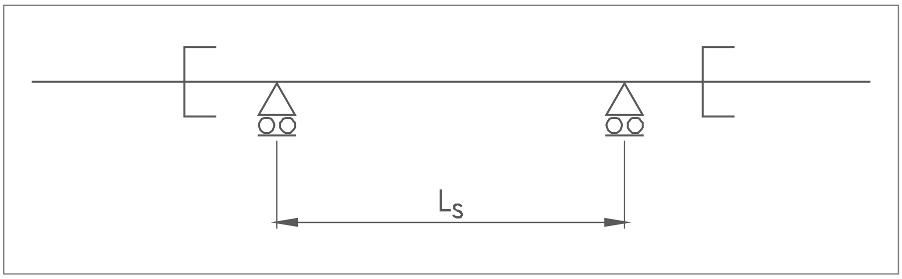


Fig. III.3. Single span length

The single span length (L_S) should be used in each of the following situations (see fig. III.5.):

- Pipe systems where the joint is not designed to transmit bending moments; this is the case for mechanical couplers, flanged joints and the rubber seal (lock) joints.
- Once at the location of a change of direction itself.
- Once on each side of any change of direction.

The single span length (L_S) is calculated using the following formulas:

A. Single span length based on the axial stress:

$$L_{S1} = \sqrt{\frac{8 \times W_B \times S_A}{Q_P}}$$

(Eq. III.1.)

Where:
L_{S1} = Single span length based on axial stress (mm)
W_B = Moment of resistance to bending (see tables II-b. and II-c.) (mm^3)
S_A = Remaining axial stress (N/mm^2)
Q_P = Linear weight of filled pipe (see Eq. III.5.) (N/mm)

The value of the remaining axial stress (SA) depends on the actual stress due to internal pressure:

$$S_A = S_{XT} - S_X$$

(Eq. III.2.)

Where:
S_A = Remaining axial stress (N/mm^2)
S_{XT} = Allowable axial stress (see table II-m.) (N/mm^2)
S_X = Actual axial stress due to internal pressure (N/mm^2)

The value of the actual axial stress due to internal pressure (SX) depends on the type of loading of the pipeline system and is derived from equation III.3. or III.4.

For bi-axial loaded systems:

$$S_x = \frac{P}{4} \times \left(\frac{ID}{T_E} + 1\right)$$

(Eq. III.3.)

For uni-axial loaded systems:

$$S_x = \frac{P}{8} \times \left(\frac{ID}{T_E} + 1\right)$$

(Eq. III.4.)

Where:
S_X = Actual axial stress due to internal pressure (N/mm^2)
P = Operating pressure (MPa)
ID = Inner diameter (mm)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (mm)

The value of QP depends on the type of fluid that is transported:

$$Q_p = \frac{(G_B \times G_V) \times g}{1000}$$

(Eq. III.5.)

Where:
Q_P = Linear weight of the filled pipe (N/mm)
G_B = Linear mass of the pipe (see tables II-b. and II-c.) (kg/m)
G_V = Linear mass of the pipe content (see table II-d.) (kg/m)
g = Acceleration due to gravity (m/s^2)

B. Single span length based on the allowable sag:

$$L_{S2} = 0.7268 \times \sqrt[3]{\frac{E_{XT} \times I_Z}{Q_P}}$$

(Eq. III.6.)

Where:
L_{S2} = Single span length based on the allowable sag (mm)
E_{XT} = Axial bending modulus at elevated temperature (see Eq. III.7.) (N/mm^2)
I_Z = Linear moment of inertia (see tables II-b. and II-c.) (mm^4)
Q_P = Linear weight of the filled pipe (see Eq. III.5.) (N/mm)

At operating temperatures in excess of 21 °C the temperature correction factor for the E-modulus (RE) (see table II-h.) shall be applied as follows:

$$E_{XT} = E_X \times R_E$$

(Eq. III.7.)

Where:
E_{XT} = Axial bending modulus at elevated temperature (N/mm2)
E_X = Axial bending modulus (see table II-g.) (N/mm2)
R_E = Temperature correction factor (RE1, RE2, RE3) for E-modulus (see table II-h.). (-)

The single span length (LS) will be the lowest value of L_{S1} and L_{S2}.

III.4.2. Continuous span length

The continuous span length (L_C) is the length between two supports of a string of rigid jointed pipes (see fig. III.4.).

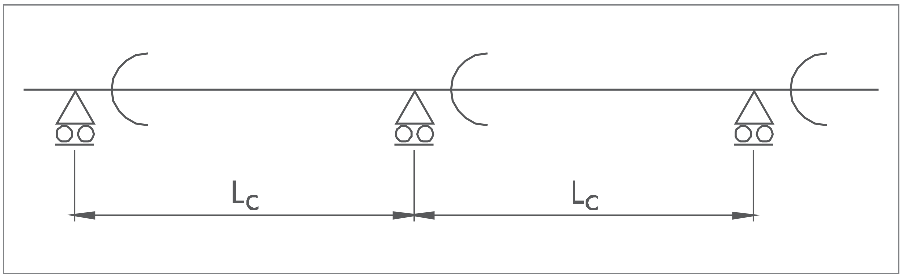


Fig. III.4. Continuous span length

The continuous span length (L_C) may be used for pipe systems where the joint is rigid and capable of transmitting bending forces. This continuous span length (L_C) can be used for adhesive bonded and laminated pipe systems.

The continuous span length (L_C) is calculated using the following formulas:

A. Continuous span length based on the axial stress:

$$L_{C1} = \sqrt{\frac{12 \times W_B \times S_A}{Q_P}}$$

(Eq. III.8.)

Where:
L_{C1} = Continuous span length based on axial stress (mm)
W_B = Moment of resistance to bending (see tables II-b. and II-c.) (mm^3)
S_A = Remaining axial stress (see Eq. III.2.) (N/mm^2)
Q_P = Linear weight of filled pipe (see Eq. III.5.) (N/mm)

Substitution of Eq. III.1. in Eq. III.8. results in the following equation:

$$L_{C1} = 1.225 \times L_{S1}$$

(Eq. III.9.)

B. Continuous span length based on the allowable sag:

$$L_{c2} = 1.2429 \times \sqrt[3]{\frac{E_{XT} \times I_Z}{Q_P}}$$

(Eq. III.10.)

Where:
L_{C2} = Continuous span length based on the allowable sag (mm)
E_{XT} = Axial bending modulus at elevated temperature (see Eq. III.7.) (N/mm^2)
I_Z = Linear moment of inertia (see tables II-b. and II-c.) (mm^4)
Q_P = Linear weight of the filled pipe (see Eq. III.5.) (N/mm)

Substitution of Eq. III.6. in Eq. III.10. results in the following equation:

$$L_{C2} = 1.71 \times L_{S2}$$

(Eq. III.11.)

The continuous span length (L_C) will be the lowest value of L_{C1} and L_{C2}.

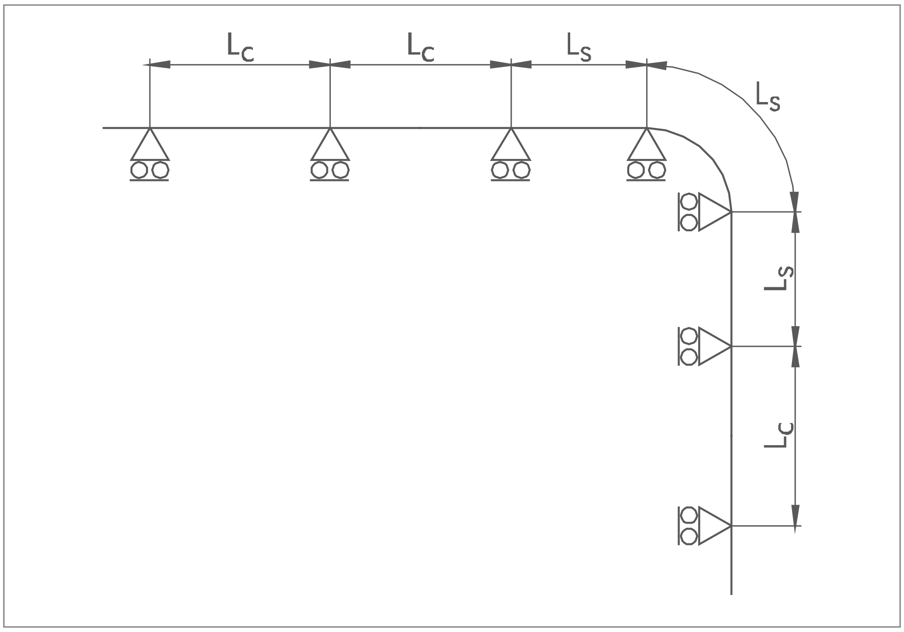


Fig. III.5. Examples of single span length (L_S) and continuous span length L_C)

III.5. Corrected support distance

Depending on the operating conditions of the pipeline, the values of tables III-c. through III-e. shall be corrected by one or both of the following correction factors:

A. Density correction factor (R_S)

Aboveground pipelines which are used for the transportation of fluids with a density (S_V) other than 1000 kg/m^3 shall be supported at a span length corrected by a factor (R_S) as shown in table III-a.

B. Temperature change correction factor (R_T)

When temperature changes occur in a straight pipeline between fixed points, the support distance shall be corrected by a factor (R_T) which is shown in table III-b.

The final support distance (L_F) is obtained from the following equation:

$L_F = L' \times R_S \times R_T$

(Eq. III.12.)

Where:

L_F = Final support distance (m)
L' = Support distance at operating temperature (T) and - pressure (P) (m)
(see tables III-c. through III-e.)
R_S = Density correction factor (see table III-a.) (-)
R_T = Temperature change correction factor (see table III-b.) (-)

Table III-a. Density correction factor Rs (-)

	Density of the fluid Sv (kg/m³)						
	0	600	800	900	1000	1100	1250
Rs	1.55	1.25	1.07	1.03	1.0	0.95	0.90

Table III-b. Temperature change correction factor RT (-)

ID (mm)	Temperature change ΔT (°C)									
	10	20	30	40	50	60	70	80	90	100
25	0.73	0.58	0.49	0.44	0.39	0.36	0.34	0.32	0.30	0.28
40	0.81	0.69	0.60	0.54	0.49	0.45	0.42	0.40	0.38	0.36
50	0.85	0.73	0.65	0.59	0.54	0.50	0.47	0.44	0.42	0.40
65	0.88	0.78	0.70	0.64	0.59	0.55	0.52	0.49	0.47	0.45
80	0.90	0.81	0.74	0.69	0.64	0.60	0.57	0.54	0.51	0.49
100	0.92	0.85	0.79	0.74	0.69	0.66	0.62	0.59	0.57	0.54
125	0.92	0.85	0.80	0.75	0.71	0.67	0.64	0.61	0.59	0.57
150	0.92	0.85	0.80	0.75	0.72	0.68	0.66	0.63	0.61	0.59
200	0.94	0.89	0.84	0.81	0.77	0.75	0.72	0.70	0.68	0.66
250	0.95	0.91	0.87	0.84	0.81	0.79	0.76	0.74	0.72	0.70
300	0.96	0.92	0.89	0.87	0.84	0.82	0.80	0.78	0.76	0.74
350	0.96	0.93	0.91	0.88	0.86	0.84	0.82	0.80	0.79	0.77
400	0.97	0.94	0.92	0.89	0.87	0.85	0.83	0.82	0.80	0.79
450	0.97	0.95	0.92	0.90	0.88	0.87	0.85	0.83	0.82	0.80
500	0.97	0.95	0.93	0.91	0.90	0.88	0.86	0.85	0.83	0.82
600	0.98	0.96	0.94	0.93	0.91	0.90	0.88	0.87	0.86	0.85
700	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.91
750	0.99	0.98	0.97	0.96	0.95	0.94	0.94	0.93	0.92	0.91
800	0.99	0.98	0.97	0.96	0.95	0.95	0.94	0.93	0.93	0.92
900	0.99	0.98	0.98	0.97	0.96	0.96	0.95	0.94	0.94	0.93
1000	0.99	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.94	0.94
1200	0.99	0.99	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.95
1400	0.99	0.99	0.99	0.98	0.98	0.97	0.97	0.96	0.96	0.95

Table III-c-1. Support distance L' (m) for series EST; P = 1 * P_N (bar)

Series	ID (mm)	Temperature (°C)									
		20	40	60	80	100	20	40	60	80	100
		Single Span Length (L_S)					Continuous Span Length (L_C)				
EST 8	350	3.8					4.7				
	400	4.1					5.0				
	450	4.3					5.3				
	500	4.6					5.6				
	600	5.0					6.1				
	700	5.4					6.6				
	750	5.6					6.9				
	800	6.0					7.4				
	900	6.3					7.8				
	1000	6.7					8.2				
	1200	7.3					8.9				
	1400	7.8					9.6				
EST 12.5	250	4.0					4.9				
	300	4.4					5.4				
	350	4.7					5.8				
	400	5.1					6.2				
	450	5.4					6.6				
	500	5.9					7.3				
	600	6.4					7.9				
	700	6.9					8.5				
	750	7.2					8.8				
	800	7.4					9.0				
	900	7.8					9.6				
	1000	8.2					10.1				
	1200	9.0					11.0				
EST 16	200	3.8					4.6				
	250	4.5					5.5				
	300	4.8					5.8				
	350	5.1					6.2				
	400	5.6					6.9				
	450	5.9					7.2				
	500	6.1					7.5				
	600	6.8					8.3				
	700	7.4					9.0				
	750	7.6					9.3				
	800	7.8					9.5				

Table III-c-2. Support distance L' (m) for series EST; P = 1 * P_N (bar) (continued)

<table>
<tr><th rowspan="3">Series</th><th rowspan="3">ID (mm)</th><th colspan="10">Temperature (°C)</th></tr>
<tr><th>20</th><th>40</th><th>60</th><th>80</th><th>100</th><th>20</th><th>40</th><th>60</th><th>80</th><th>100</th></tr>
<tr><th colspan="5">Single Span Length (L_S)</th><th colspan="5">Continuous Span Length (L_C)</th></tr>
<tr><td rowspan="12">EST 20</td><td>150</td><td colspan="3">3.8</td><td>3.8</td><td>3.7</td><td colspan="5">4.6</td></tr>
<tr><td>200</td><td colspan="3">4.7</td><td>4.6</td><td>4.5</td><td colspan="5">5.7</td></tr>
<tr><td>250</td><td colspan="3">5.2</td><td>5.2</td><td>5.2</td><td colspan="5">6.4</td></tr>
<tr><td>300</td><td colspan="3">5.6</td><td>5.6</td><td>5.6</td><td colspan="5">6.9</td></tr>
<tr><td>350</td><td colspan="3">6.1</td><td>6.1</td><td>6.1</td><td colspan="5">7.4</td></tr>
<tr><td>400</td><td colspan="3">6.5</td><td>6.5</td><td>6.5</td><td colspan="5">7.9</td></tr>
<tr><td>450</td><td colspan="3">6.8</td><td>6.8</td><td>6.8</td><td colspan="5">8.4</td></tr>
<tr><td>500</td><td colspan="3">7.2</td><td>7.2</td><td>7.2</td><td colspan="5">8.8</td></tr>
<tr><td>600</td><td colspan="3">8.0</td><td>8.0</td><td>8.0</td><td colspan="5">9.8</td></tr>
<tr><td>700</td><td colspan="3">8.6</td><td>8.6</td><td>8.6</td><td colspan="5">10.5</td></tr>
<tr><td>750</td><td colspan="3">8.9</td><td>8.9</td><td>8.9</td><td colspan="5">10.9</td></tr>
<tr><td>800</td><td colspan="3">9.1</td><td>9.1</td><td>9.1</td><td colspan="5">11.2</td></tr>
<tr><td rowspan="11">EST 25</td><td>100</td><td>3.5</td><td>3.4</td><td>3.4</td><td>3.3</td><td>3.2</td><td colspan="3">5.7</td><td>5.6</td><td>5.4</td></tr>
<tr><td>125</td><td>3.9</td><td>3.8</td><td>3.7</td><td>3.6</td><td>3.5</td><td colspan="3">5.1</td><td>5.1</td><td>5.1</td></tr>
<tr><td>150</td><td>4.4</td><td>4.3</td><td>4.2</td><td>4.1</td><td>4.0</td><td colspan="3">5.5</td><td>5.5</td><td>5.5</td></tr>
<tr><td>200</td><td>5.1</td><td>5.1</td><td>5.1</td><td>5.0</td><td>4.8</td><td colspan="3">6.2</td><td>6.2</td><td>6.2</td></tr>
<tr><td>250</td><td>5.6</td><td>5.6</td><td>5.6</td><td>5.6</td><td>5.6</td><td colspan="3">6.9</td><td>6.9</td><td>6.9</td></tr>
<tr><td>300</td><td>6.1</td><td>6.1</td><td>6.1</td><td>6.1</td><td>6.1</td><td colspan="3">7.5</td><td>7.5</td><td>7.5</td></tr>
<tr><td>350</td><td>6.6</td><td>6.6</td><td>6.6</td><td>6.6</td><td>6.6</td><td colspan="3">8.1</td><td>8.1</td><td>8.1</td></tr>
<tr><td>400</td><td>7.2</td><td>7.2</td><td>7.2</td><td>7.2</td><td>7.2</td><td colspan="3">8.8</td><td>8.8</td><td>8.8</td></tr>
<tr><td>450</td><td>7.6</td><td>7.6</td><td>7.6</td><td>7.6</td><td>7.6</td><td colspan="3">9.3</td><td>9.3</td><td>9.3</td></tr>
<tr><td>500</td><td>8.0</td><td>8.0</td><td>8.0</td><td>8.0</td><td>8.0</td><td colspan="3">9.8</td><td>9.8</td><td>9.8</td></tr>
<tr><td>600</td><td>8.7</td><td>8.7</td><td>8.7</td><td>8.7</td><td>8.7</td><td colspan="3">10.7</td><td>10.7</td><td>10.7</td></tr>
<tr><td rowspan="9">EST 32</td><td>80</td><td>3.2</td><td>3.2</td><td>3.1</td><td>3.0</td><td>2.9</td><td>5.5</td><td>5.4</td><td>5.3</td><td>5.2</td><td>5.0</td></tr>
<tr><td>100</td><td>3.6</td><td>3.5</td><td>3.5</td><td>3.4</td><td>3.2</td><td>4.7</td><td>4.7</td><td>4.7</td><td>4.7</td><td>4.7</td></tr>
<tr><td>125</td><td>4.2</td><td>4.1</td><td>4.0</td><td>3.9</td><td>3.7</td><td>5.1</td><td>5.1</td><td>5.1</td><td>5.1</td><td>5.1</td></tr>
<tr><td>150</td><td>4.5</td><td>4.5</td><td>4.5</td><td>4.4</td><td>4.2</td><td>5.5</td><td>5.5</td><td>5.5</td><td>5.5</td><td>5.5</td></tr>
<tr><td>200</td><td>5.3</td><td>5.3</td><td>5.3</td><td>5.3</td><td>5.1</td><td>6.4</td><td>6.4</td><td>6.4</td><td>6.4</td><td>6.4</td></tr>
<tr><td>250</td><td>5.9</td><td>5.9</td><td>5.9</td><td>5.9</td><td>5.9</td><td>7.3</td><td>7.3</td><td>7.3</td><td>7.3</td><td>7.3</td></tr>
<tr><td>300</td><td>6.6</td><td>6.6</td><td>6.6</td><td>6.6</td><td>6.6</td><td>8.0</td><td>8.0</td><td>8.0</td><td>8.0</td><td>8.0</td></tr>
<tr><td>350</td><td>7.1</td><td>7.1</td><td>7.1</td><td>7.1</td><td>7.1</td><td>8.7</td><td>8.7</td><td>8.7</td><td>8.7</td><td>8.7</td></tr>
<tr><td>400</td><td>7.6</td><td>7.6</td><td>7.6</td><td>7.6</td><td>7.6</td><td>9.3</td><td>9.3</td><td>9.3</td><td>9.3</td><td>9.3</td></tr>
</table>

Table III-c-3. Support distance L' (m) for series EST; P = 1 * P_N (bar) (continued)

Series	ID (mm)	Temperature (°C)									
		20	40	60	80	100	20	40	60	80	100
		Single Span Length (L_S)					Continuous Span Length (L_C)				
EST 40	50	2.5	2.4	2.4	2.3	2.2	4.3	4.2	4.1	4.0	3.8
	65	3.0	2.9	2.9	2.8	2.7	5.1	5.0	4.9	4.8	4.6
	80	3.3	3.2	3.2	3.1	3.0	4.6	4.6	4.6	4.6	4.6
	100	3.9	3.8	3.7	3.6	3.5	5.3	5.3	5.3	5.3	5.3
	125	4.5	4.4	4.3	4.2	4.0	5.9	5.9	5.9	5.9	5.9
	150	5.1	5.0	4.9	4.7	4.6	6.7	6.7	6.7	6.7	6.7
	200	6.2	6.0	5.9	5.7	5.5	7.6	7.6	7.6	7.6	7.6
	250	7.0	7.0	6.9	6.7	6.4	8.6	8.6	8.6	8.6	8.6
	300	7.6	7.6	7.6	7.5	7.3	9.3	9.3	9.3	9.3	9.3
	350	8.3	8.3	8.3	8.3	8.1	10.1	10.1	10.1	10.1	10.1
	400	8.8	8.8	8.8	8.8	8.8	10.7	10.7	10.7	10.7	10.7
EST 50	25	1.9	1.9	1.8	1.8	1.7	3.3	3.2	3.1	3.0	2.9
	40	2.3	2.2	2.2	2.1	2.1	3.9	3.8	3.7	3.6	3.5
	50	2.6	2.5	2.5	2.4	2.3	4.2	4.2	4.2	4.1	4.0
	65	3.1	3.0	3.0	2.9	2.8	4.7	4.7	4.7	4.7	4.7
	80	3.6	3.5	3.4	3.3	3.2	5.1	5.1	5.1	5.1	5.1
	100	4.2	4.1	4.0	3.9	3.7	6.0	6.0	6.0	6.0	6.0
	125	4.8	4.7	4.6	4.5	4.3	6.5	6.5	6.5	6.5	6.5
	150	5.5	5.3	5.2	5.1	4.9	7.3	7.3	7.3	7.3	7.3
	200	6.6	6.5	6.3	6.1	5.9	8.3	8.3	8.3	8.3	8.3
	250	7.6	7.5	7.3	7.1	6.9	9.3	9.3	9.3	9.3	9.3
	300	8.4	8.4	8.3	8.1	7.8	10.2	10.2	10.2	10.2	10.2
	350	9.1	9.1	9.1	8.9	8.6	11.1	11.1	11.1	11.1	11.1
	400	9.7	9.7	9.7	9.7	9.4	11.9	11.9	11.9	11.9	11.9

Table III-d-1. Support distance L' (m) for series EST; P= 0.75 * P_N (bar)

Series	ID (mm)	Temperature (°C)									
		20	40	60	80	100	20	40	60	80	100
		Single Span Length (L_s)					Continuous Span Length (L_c)				
EST 8	350	5.3				5.1	6.5				
	400	5.7				5.6	7.0				
	450	6.0				6.0	7.4				
	500	6.4				6.4	7.8				
	600	7.0				7.0	8.5				
	700	7.5				7.5	9.2				
	750	7.8				7.8	9.5				
	800	8.2				8.2	10.0				
	900	8.7				8.7	10.6				
	1000	9.1				9.1	11.2				
	1200	10.0				10.0	12.2				
	1400	10.8				10.8	13.2				
EST 12.5	250	5.0	4.8	4.7	4.6	4.4	6.8				
	300	5.6	5.5	5.3	5.2	5.0	7.5				
	350	6.2	6.1	5.9	5.8	5.6	8.1				
	400	6.8	6.6	6.5	6.3	6.1	8.6				
	450	7.3	7.2	7.0	6.8	6.6	9.2				
	500	7.9	7.7	7.6	7.4	7.1	9.9				
	600	8.8	8.7	8.5	8.3	8.0	10.8				
	700	9.5	9.5	9.5	9.2	8.9	11.6				
	750	9.8	9.8	9.8	9.6	9.3	12.0				
	800	10.1	10.1	10.1	10.1	9.7	12.4				
	900	10.7	10.7	10.7	10.7	10.5	13.1				
	1000	11.3	11.3	11.3	11.3	11.3	13.8				
	1200	12.4	12.4	12.4	12.4	12.4	15.1				
EST 16	200	4.6	4.5	4.4	4.3	4.1	6.6				
	250	5.4	5.2	5.1	5.0	4.8	7.6				
	300	6.0	5.9	5.8	5.6	5.4	8.3				
	350	6.7	6.5	6.4	6.2	6.0	8.8				
	400	7.3	7.2	7.0	6.8	6.6	9.6				
	450	7.9	7.7	7.6	7.4	7.1	10.1				
	500	8.5	8.3	8.1	7.9	7.6	10.6				
	600	9.6	9.4	9.2	8.9	8.6	11.7				
	700	10.4	10.4	10.2	9.9	9.6	12.7				
	750	10.7	10.7	10.6	10.3	10.0	13.1				
	800	11.0	11.0	11.0	10.8	10.4	13.5				

Table III-d-2. Support distance L' (m) for series EST; P= 0.75 * PN (bar) (continued)

Series	ID (mm)	Temperature (°C)									
		20	40	60	80	100	20	40	60	80	100
		Single Span Length (Ls)					Continuous Span Length (Lc)				
EST 20	150	4.1	4.0	3.9	3.8	3.7	6.5				6.3
	200	5.0	4.9	4.8	4.6	4.5	7.8				7.7
	250	5.8	5.7	5.5	5.4	5.2	8.7				8.7
	300	6.5	6.4	6.2	6.1	5.9	9.5				9.5
	350	7.3	7.1	6.9	6.7	6.5	10.2				10.2
	400	7.9	7.7	7.6	7.4	7.1	10.9				10.9
	450	8.6	8.4	8.2	8.0	7.7	11.5				11.5
	500	9.2	9.0	8.8	8.5	8.2	12.1				12.1
	600	10.4	10.2	9.9	9.7	9.3	13.4				13.4
	700	11.5	11.2	11.0	10.7	10.3	14.5				14.5
	750	12.1	11.8	11.5	11.2	10.8	14.9				14.9
	800	12.6	12.3	12.0	11.7	11.3	15.4				15.4
EST 25	100	3.5	3.4	3.4	3.3	3.2	6.0	5.9	5.8	5.6	5.4
	125	3.9	3.8	3.7	3.6	3.5	6.7	6.5	6.4	6.2	6.0
	150	4.4	4.3	4.2	4.1	4.0	7.4	7.4	7.2	7.0	6.8
	200	5.4	5.2	5.1	5.0	4.8	8.5	8.5	8.5	8.5	8.2
	250	6.2	6.1	5.9	5.8	5.6	9.5	9.5	9.5	9.5	9.5
	300	7.0	6.8	6.7	6.5	6.3	10.4	10.4	10.4	10.4	10.4
	350	7.8	7.6	7.4	7.2	7.0	11.2	11.2	11.2	11.2	11.2
	400	8.5	8.3	8.1	7.9	7.6	12.1	12.1	12.1	12.1	12.1
	450	9.2	9.0	8.8	8.5	8.3	12.8	12.8	12.8	12.8	12.8
	500	9.9	9.6	9.4	9.2	8.8	13.5	13.5	13.5	13.5	13.5
	600	11.1	10.9	10.6	10.3	10.0	14.7	14.7	14.7	14.7	14.7
EST 32	80	3.2	3.2	3.1	3.0	2.9	5.6	5.4	5.3	5.2	5.0
	100	3.6	3.5	3.5	3.4	3.2	6.2	6.0	5.9	5.7	5.5
	125	4.2	4.1	4.0	3.9	3.7	7.1	7.0	6.8	6.6	6.4
	150	4.7	4.6	4.5	4.4	4.2	7.9	7.9	7.7	7.5	7.2
	200	5.7	5.6	5.5	5.3	5.1	9.2	9.2	9.2	9.1	8.8
	250	6.7	6.5	6.4	6.2	6.0	10.3	10.3	10.3	10.3	10.2
	300	7.5	7.3	7.2	7.0	6.7	11.3	11.3	11.3	11.3	11.3
	350	8.3	8.1	8.0	7.7	7.5	12.3	12.3	12.3	12.3	12.3
	400	9.1	8.9	8.7	8.5	8.2	13.2	13.2	13.2	13.2	13.2

Table III-d-3. Support distance L' (m) for series EST; P= 0.75 * P_N (bar) (continued)

Series	ID (mm)	Temperature (°C)									
		20	40	60	80	100	20	40	60	80	100
		Single Span Length (L_S)					Continuous Span Length (L_C)				
EST 40	50	2.5	2.4	2.4	2.3	2.2	4.3	4.2	4.1	4.0	3.8
	65	3.0	2.9	2.9	2.8	2.7	5.1	5.0	4.9	4.8	4.6
	80	3.3	3.2	3.2	3.1	3.0	5.7	5.6	5.4	5.3	5.1
	100	3.9	3.8	3.7	3.6	3.5	6.6	6.5	6.3	6.2	6.0
	125	4.5	4.4	4.3	4.2	4.0	7.7	7.5	7.4	7.2	6.9
	150	5.1	5.0	4.9	4.7	4.6	8.7	8.5	8.4	8.1	7.8
	200	6.2	6.0	5.9	5.7	5.5	10.4	10.3	10.1	9.8	9.5
	250	7.2	7.0	6.9	6.7	6.4	11.8	11.8	11.7	11.4	11.0
	300	8.1	7.9	7.7	7.5	7.3	12.8	12.8	12.8	12.8	12.4
	350	9.0	8.8	8.6	8.4	8.1	13.9	13.9	13.9	13.9	13.8
	400	9.8	9.6	9.4	9.1	8.8	14.8	14.8	14.8	14.8	14.8
EST 50	25	1.9	1.9	1.8	1.8	1.7	3.3	3.2	3.1	3.0	2.9
	40	2.3	2.2	2.2	2.1	2.1	3.9	3.8	3.7	3.6	3.5
	50	2.6	2.5	2.5	2.4	2.3	4.5	4.4	4.3	4.1	4.0
	65	3.1	3.0	3.0	2.9	2.8	5.3	5.2	5.1	4.9	4.8
	80	3.6	3.5	3.4	3.3	3.2	6.1	6.0	5.8	5.7	5.5
	100	4.2	4.1	4.0	3.9	3.7	7.1	7.0	6.8	6.6	6.4
	125	4.8	4.7	4.6	4.5	4.3	8.3	8.1	7.9	7.7	7.4
	150	5.5	5.3	5.2	5.1	4.9	9.4	9.1	8.9	8.7	8.4
	200	6.6	6.5	6.3	6.1	5.9	11.3	11.0	10.8	10.5	10.1
	250	7.7	7.5	7.3	7.1	6.9	12.8	12.8	12.6	12.2	11.8
	300	8.7	8.5	8.3	8.1	7.8	14.1	14.1	14.1	13.8	13.3
	350	9.6	9.4	9.2	8.9	8.6	15.3	15.3	15.3	15.3	14.8
	400	10.5	10.3	10.1	9.8	9.4	16.3	16.3	16.3	16.3	16.2

Table III-e-1. Support distance L' (m) for series EST; P= 0.5 * PN (bar)

Series	ID (mm)	Temperature (°C)									
		20	40	60	80	100	20	40	60	80	100
		Single Span Length (Ls)					Continuous Span Length (Lc)				
EST 8	350	5.7	5.6	5.4	5.3	5.1	7.9				
	400	6.2	6.1	5.9	5.8	5.6	8.5				
	450	6.7	6.6	6.4	6.2	6.0	9.0				
	500	7.2	7.0	6.9	6.7	6.5	9.5				
	600	8.2	8.0	7.8	7.6	7.3	10.4				
	700	9.0	8.8	8.6	8.4	8.1	11.2				
	750	9.5	9.2	9.0	8.8	8.5	11.6				
	800	9.9	9.7	9.5	9.2	8.9	12.1				
	900	10.5	10.5	10.3	10.0	9.6	12.9				
	1000	11.1	11.1	11.0	10.7	10.3	13.6				
	1200	12.1	12.1	12.1	12.1	11.7	14.8				
	1400	13.1	13.1	13.1	13.1	12.9	16.0				
EST 12.5	250	5.0	4.8	4.7	4.6	4.4	8.3	8.3	8.1	7.9	7.6
	300	5.6	5.5	5.3	5.2	5.0	9.1	9.1	9.1	8.9	8.6
	350	6.2	6.1	5.9	5.8	5.6	9.8	9.8	9.8	9.8	9.5
	400	6.8	6.6	6.5	6.3	6.1	10.5	10.5	10.5	10.5	10.4
	450	7.3	7.2	7.0	6.8	6.6	11.2	11.2	11.2	11.2	11.2
	500	7.9	7.7	7.6	7.4	7.1	11.9	11.9	11.9	11.9	11.9
	600	9.0	8.7	8.5	8.3	8.0	13.1	13.1	13.1	13.1	13.1
	700	9.9	9.7	9.5	9.2	8.9	14.1	14.1	14.1	14.1	14.1
	750	10.4	10.1	9.9	9.6	9.3	14.6	14.6	14.6	14.6	14.6
	800	10.8	10.6	10.3	10.1	9.7	15	15	15	15	15
	900	11.7	11.4	11.2	10.9	10.5	15.9	15.9	15.9	15.9	15.9
	1000	12.6	12.3	12.0	11.7	11.3	16.8	16.8	16.8	16.8	16.8
	1200	14.2	13.8	13.5	13.2	12.7	18.4	18.4	18.4	18.4	18.4
EST 16	200	4.6	4.5	4.4	4.3	4.1	7.8	7.7	7.5	7.3	7
	250	5.4	5.2	5.1	5	4.8	9.2	9	8.8	8.5	8.2
	300	6	5.9	5.8	5.6	5.4	10.1	10.1	9.9	9.6	9.3
	350	6.7	6.5	6.4	6.2	6	10.9	10.9	10.9	10.6	10.2
	400	7.3	7.2	7	6.8	6.6	11.7	11.7	11.7	11.7	11.2
	450	7.9	7.7	7.6	7.4	7.1	12.4	12.4	12.4	12.4	12.1
	500	8.5	8.3	8.1	7.9	7.6	13	13	13	13	13
	600	9.6	9.4	9.2	8.9	8.6	14.3	14.3	14.3	14.3	14.3
	700	10.7	10.4	10.2	9.9	9.6	15.5	15.5	15.5	15.5	15.5
	750	11.1	10.9	10.6	10.3	10	16	16	16	16	16
	800	11.6	11.3	11.1	10.8	10.4	16.5	16.5	16.5	16.5	16.5

Table III-e-2. Support distance L' (m) for series EST; P= 0.5 * PN (bar) (continued)

Series	ID (mm)	Temperature (°C)									
		20	40	60	80	100	20	40	60	80	100
		Single Span Length (Ls)					Continuous Span Length (Lc)				
EST 20	150	4.1	4	3.9	3.8	3.7	7	6.8	6.7	6.5	6.3
	200	5	4.9	4.8	4.6	4.5	8.6	8.4	8.2	7.9	7.7
	250	5.8	5.7	5.5	5.4	5.2	9.9	9.7	9.5	9.2	8.9
	300	6.5	6.4	6.2	6.1	5.9	11.2	10.9	10.7	10.4	10
	350	7.3	7.1	6.9	6.7	6.5	12.4	12.1	11.8	11.5	11.1
	400	7.9	7.7	7.6	7.4	7.1	13.2	13.2	12.9	12.6	12.1
	450	8.6	8.4	8.2	8	7.7	14	14	14	13.6	13.1
	500	9.2	9	8.8	8.5	8.2	14.7	14.7	14.7	14.6	14.1
	600	10.4	10.2	9.9	9.7	9.3	16.3	16.3	16.3	16.3	15.9
	700	11.5	11.2	11	10.7	10.3	17.5	17.5	17.5	17.5	17.5
	750	12.1	11.8	11.5	11.2	10.8	18.1	18.1	18.1	18.1	18.1
	800	12.6	12.3	12	11.7	11.3	18.7	18.7	18.7	18.7	18.7
EST 25	100	3.5	3.4	3.4	3.3	3.2	6	5.9	5.8	5.6	5.4
	125	3.9	3.8	3.7	3.6	3.5	6.7	6.5	6.4	6.2	6.0
	150	4.4	4.3	4.2	4.1	4	7.6	7.4	7.2	7	6.8
	200	5.4	5.2	5.1	5	4.8	9.2	8.9	8.7	8.5	8.2
	250	6.2	6.1	5.9	5.8	5.6	10.6	10.4	10.1	9.9	9.5
	300	7	6.8	6.7	6.5	6.3	12	11.7	11.4	11.1	10.7
	350	7.8	7.6	7.4	7.2	7.0	13.3	13	12.7	12.3	11.9
	400	8.5	8.3	8.1	7.9	7.6	14.6	14.2	13.9	13.5	13.1
	450	9.2	9.0	8.8	8.5	8.3	15.5	15.4	15	14.6	14.1
	500	9.9	9.6	9.4	9.2	8.8	16.4	16.4	16.1	15.7	15.1
	600	11.1	10.9	10.6	10.3	10	17.9	17.9	17.9	17.7	17.1
EST 32	80	3.2	3.2	3.1	3.0	2.9	5.6	5.4	5.3	5.2	5.0
	100	3.6	3.5	3.5	3.4	3.2	6.2	6.0	5.9	5.7	5.5
	125	4.2	4.1	4.0	3.9	3.7	7.1	7.0	6.8	6.6	6.4
	150	4.7	4.6	4.5	4.4	4.2	8.1	7.9	7.7	7.5	7.2
	200	5.7	5.6	5.5	5.3	5.1	9.8	9.6	9.3	9.1	8.8
	250	6.7	6.5	6.4	6.2	6.0	11.4	11.1	10.9	10.6	10.2
	300	7.5	7.3	7.2	7.0	6.7	12.9	12.6	12.3	11.9	11.5
	350	8.3	8.1	8.0	7.7	7.5	14.3	13.9	13.6	13.3	12.8
	400	9.1	8.9	8.7	8.5	8.2	15.6	15.2	14.9	14.5	14.0

Table III-e-3. Support distance L' (m) for series EST; P= 0.5 * PN (bar) (continued)

Series	ID (mm)	Temperature (°C)									
		20	40	60	80	100	20	40	60	80	100
		Single Span Length (Ls)					Continuous Span Length (Lc)				
EST 40	50	2.5	2.4	2.4	2.3	2.2	4.3	4.2	4.1	4.0	3.8
	65	3.0	2.9	2.9	2.8	2.7	5.1	5.0	4.9	4.8	4.6
	80	3.3	3.2	3.2	3.1	3.0	5.7	5.6	5.4	5.3	5.1
	100	3.9	3.8	3.7	3.6	3.5	6.6	6.5	6.3	6.2	6.0
	125	4.5	4.4	4.3	4.2	4.0	7.7	7.5	7.4	7.2	6.9
	150	5.1	5.0	4.9	4.7	4.6	8.7	8.5	8.4	8.1	7.8
	200	6.2	6.0	5.9	5.7	5.5	10.6	10.3	10.1	9.8	9.5
	250	7.2	7.0	6.9	6.7	6.4	12.3	12.0	11.7	11.4	11.0
	300	8.1	7.9	7.7	7.5	7.3	13.9	13.5	13.2	12.9	12.4
	350	9.0	8.8	8.6	8.4	8.1	15.4	15.0	14.7	14.3	13.8
	400	9.8	9.6	9.4	9.1	8.8	16.8	16.4	16.1	15.6	15.1
EST 50	25	1.9	1.9	1.8	1.8	1.7	3.3	3.2	3.1	3.0	2.9
	40	2.3	2.2	2.2	2.1	2.1	3.9	3.8	3.7	3.6	3.5
	50	2.6	2.5	2.5	2.4	2.3	4.5	4.4	4.3	4.1	4.0
	65	3.1	3.0	3.0	2.9	2.8	5.3	5.2	5.1	4.9	4.8
	80	3.6	3.5	3.4	3.3	3.2	6.1	6.0	5.8	5.7	5.5
	100	4.2	4.1	4.0	3.9	3.7	7.1	7.0	6.8	6.6	6.4
	125	4.8	4.7	4.6	4.5	4.3	8.3	8.1	7.9	7.7	7.4
	150	5.5	5.3	5.2	5.1	4.9	9.4	9.1	8.9	8.7	8.4
	200	6.6	6.5	6.3	6.1	5.9	11.3	11.0	10.8	10.5	10.1
	250	7.7	7.5	7.3	7.1	6.9	13.2	12.8	12.6	12.2	11.8
	300	8.7	8.5	8.3	8.1	7.8	14.9	14.5	14.2	13.8	13.3
	350	9.6	9.4	9.2	8.9	8.6	16.5	16.1	15.7	15.3	14.8
	400	10.5	10.3	10.1	9.8	9.4	18.0	17.6	17.2	16.7	16.2

III.6. Anchor points

Anchor points are used to fix a certain point of the pipeline system. The expansion of the pipeline system is directed from the fixed point towards the required direction; this pipeline with the supports shall be able to move freely together.

Anchor points can be created as follows:

A. Adhesive bonded saddle

Adhesive saddles can be bonded at the bottom of the pipe at both sides of a pipe clamp.

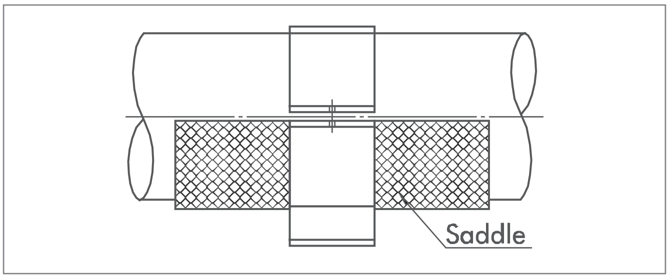


Fig. III.6. Adhesive bonded anchor

B. Laminate build-ups

A laminate is wrapped at both sides of a pipe clamp.

Two half-moon adhesive saddles also acceptable for diameters up to DN400.

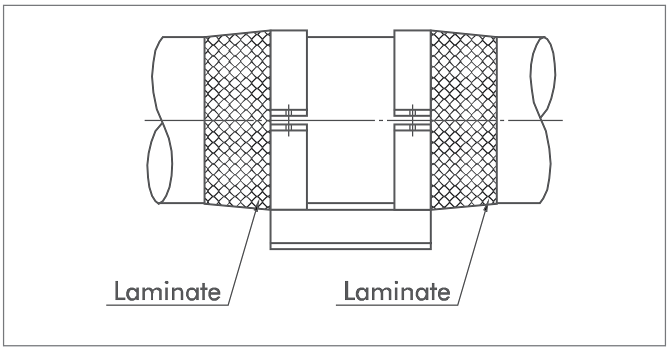


Fig. III.7. Laminated anchor

III.7. Anchor loads

Although Wavistrong pipes have a higher coefficient of linear thermal expansion (Υ_L) than steel pipes, their far lower axial E-modulus results in comparatively low expansion forces at the anchor points when subjected to temperature changes (ΔT).

Table III-f. shows the anchor loads (PA) for series EST at a temperature change ΔT= 10 °C, from 10 °C – 21 °C. The data is obtained from calculations with Eq. III.13., using the E-modulus at the highest temperature which is 21 °C.

$$P_A = \frac{\pi}{4} x(OD^2\text{-}ID^2)\ E_X \ x\ \Upsilon_L \ x\ \Delta T$$

(Eq. III.13.)

Where:

P_A = Anchor load (N)
OD = Outer diameter (see section II.5.1.B.) (mm)
ID = Inner diameter (mm)
E_X = Axial tensile modulus (see table II-g.) (N/mm²)
Υ_L = Coefficient of linear thermal expansion (see table II-j.) (mm/mm.°C)
ΔT = Temperature change of 10 (°C)

Anchor loads at temperature changes greater than 10 °C are to be used from the data listed in table III-f.
The anchor load (PA) in table III-f. has to be multiplied by a factor representing the multiple of 10 degrees temperature raise (ΔT/10) and the temperature correction factor for the E-modulus (R_E) at elevated temperature.

The method to calculate the anchor load at a temperature change greater than 10 °C (P_{AT}) is presented in Eq. III.14.

$$P_{AT} = P_A \times \frac{\Delta T}{10} \times R_E$$

(Eq. III.14.)

Where:
P_{AT} = Anchor load at elevated temperature (N)
P_A = Anchor load (see Eq. III.13.) (N)
ΔT = Temperature change (°C)
R_E = Temperature correction factor at elevated temperature (see table II-h.) (-)

As a rule no expansion loops or compensators are required in the pipe line. The distance between the supports should be reduced when there is a risk of axial buckling due to increasing axial stresses (see section III.5.). However, when the expansion forces on the anchor point are considered to be excessively high, reduction of the load can be found by using compensators or expansion loops. The engineers of Future Pipe Industries can give you help or further advice.

Table III-f. Anchor load PA (N) for series EST at 21 °C and ΔT= 10 °C

ID (mm)	Series EST							
	8	12.5	16	20	25	32	40	50
25								473
40								731
50							902	1012
65							1440	1582
80						1756	1871	2275
100					2179	2319	2816	3464
125					2880	3404	4199	5186
150				3234	3960	4692	5962	7359
200			4426	5521	6624	8015	10125	12553
250		5515	6703	8240	9961	12217	15555	19300
300		7616	9244	11496	13971	17300	21933	27490
350	7998	10051	12186	15288	18653	23263	29647	37124
400	10154	12819	15799	19616	24285	30105	38238	48202
450	12562	15920	19576	24480	30348			
500	15224	19692	23753	29881	37084			
600	21309	27627	33716	42700	52574			
700	28406	36895	45417	57323				
750	32335	42029	51664	65439				
800	37029	47496	58313	74091				
900	46217	59429						
1000	56418	72695						
1200	79861	103225						
1400	107357							

Table III-g. End play (mm) and angular deflection (°) of the RS(L)J

ID (mm)	End play X ♪		Deflection angle α	
	RSLJ	RSJ	RSLJ	RSJ
80	3	33	1.5°	3°
100	3	33	1.5°	3°
125	6	36 (56)	1.5°	3°
150	6	36 (56)	1.5°	3°
200	6	36 (56)	1.5°	3°
250	8	38 (58)	1.5°	3°
300	8	38 (58)	1.5°	3°
350	12	62	1.5°	3°
400	12	62	1.5°	3°
450	12	62	1.5°	3°
500	16	66	1.5°	3°
600	16	66	1.5°	2°
700	16	66	1°	2°
750	16	66	1°	2°
800	16	66	1°	2°
900	21	71	1°	2°
1000	23	73	1°	2°
1200	27	77	1°	1°
1400	32	82	1°	1°

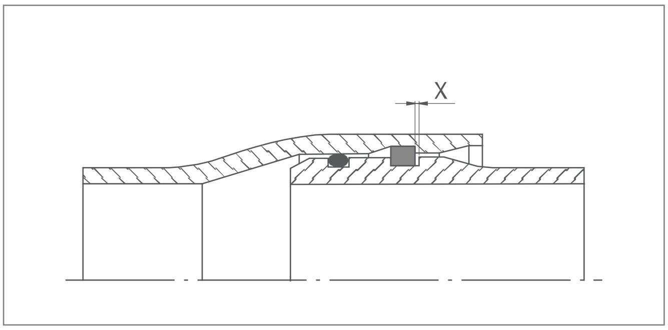


Fig. III.8. End play RSLJ

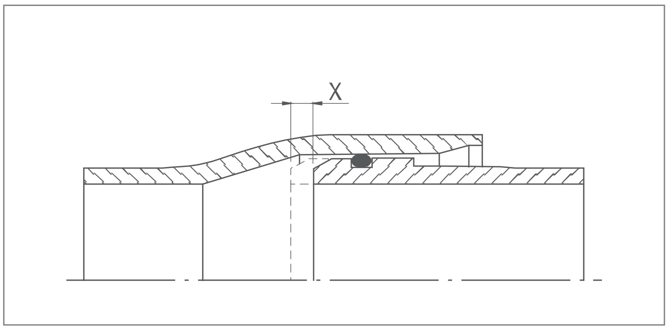


Fig. III.9. End play RSJ

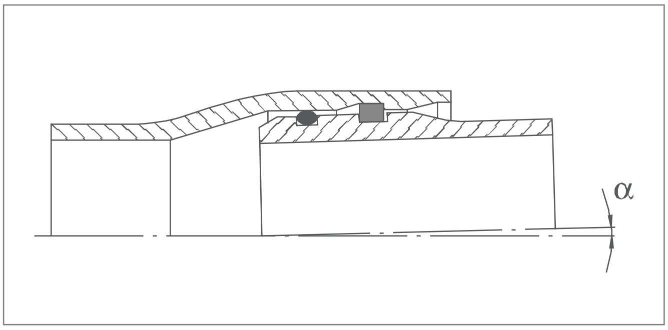


Fig. III.10. Angular deflection RS(L)J

♪ The end play is required to accommodate displacements due to soil settlement, Poisson contraction and temperature changes and therefore cannot be used for installation adjustments.
Values between brackets are valid for standard lengths of pipe Lo= 10 m

4. WAVISTRONG UNDERGROUND PIPE SYSTEMS

IV.1. Design and joining systems

When using Wavistrong pipe systems for underground applications, several types of joints can be used (see section II.4.). In contrast to aboveground pipelines, the joints of underground systems can be unrestrained (ratio axial stress/hoop stress R= 0.25).

Only at directional changes and depending on the internal pressure, inner diameter and soil conditions, some lengths of pipe should be installed with tensile resistant couplers. Alternatively an external axial restraint, e.g. a concrete anchor block, can be used.

IV.2. Anchor points

Buried, non-tensile resistant Wavistrong pipeline systems can be anchored at turns and branches by means of thrust blocks. This not only alleviates the need for expansion details, but also eliminates underground movement of the pipe system. However, in most circumstances the use of restrained couplers (e.g. rubber seal lock joint or adhesive bonded joint) over a certain length, starting from the fitting, may offer a better solution.

For this purpose, the fictive anchor length (LA) must be determined. The fictive anchor length (LA) can be calculated from the following formula:

$$L_A = 10^{-3} \times \frac{ID^2 \times P}{4 \times OD \times F_W}$$

(Eq. IV.1.)

Where:

L_A = Fictive anchor length (m)
ID = Inner diameter (mm)
P = Operating pressure (MPa)
OD = Outer diameter (see section II.5.1.B.) (mm)
F_W = Frictional stress between soil and pipe (N/mm²)

The value of the frictional stress between soil and pipe (FW) can be obtained from the soil mechanics report. If not, the following values may provide a rough indication:

- Soft clay and peaty soils: $0.001 \leq FW \leq 0.003$ (N/mm²)
- Sandy clay and sand: $0.003 \leq FW \leq 0.010$ (N/mm²)

IV.3. Calculation of underground pipe systems

Calculations of pipe deformation and data given in this section of the Engineering Guide are in line with AWWA Manual M45 ♪. Based on specific material data and with many knowledgeable years of experience this Engineering Guide may deviate from the AWWA Manual.

The stresses in the wall of a buried flexible pipe not only depend on the internal pressure, but are also a result of the deflection due to external loads. The stress resulting from the deflection depends on the interaction between the soil and the pipe, which is amongst others, directly related to the installation method.

♪ AWWA Manual M45, Latest Edition, Chapter 5

IV.3.1. Pipe deflection

The vertical deflection of an underground pipe is a function of the installation parameters, the vertical load on the pipe, the pipe stiffness and the soil characteristics.

When installed underground, a flexible pipe deflects; this means a decrease of the vertical diameter of the pipe. Many theories may be used to predict this deflection; however, in actual field conditions, pipe deflections may vary from the calculated values because theories cannot anticipate all the parameters associated with a given installation. These variations include the inherent variability of native ground conditions and variations in methods, materials and equipment used to install a buried pipe.

A prediction of the deflection is made using the following form of the Iowa formula:

$$\frac{\Delta_Y}{D} = \frac{(D_L \times W_C + W_L) \times K_X}{149 \times PS + 61000 \times E'}$$

(Eq. IV.2.)

Where:

Δ_Y = Predicted vertical pipe deflection (mm)
D = Mean pipe diameter (mm)
DL = Deflection lag factor (-)
WC = Vertical soil load (N/m^2)
WL = Live load (N/m^2)
K_X = Bedding coefficient (-)
PS = Pipe Stiffness (see section II.10.B.) (kPa)
E' = Modulus of soil reaction. (MPa)

Note: Δ_Y/D = Predicted vertical pipe deflection, fraction of mean diameter (%).
D = ID + 2 x T_L + T_E (see section II.5.A.).

Note: For the conversion of the PS (psi) listed in table II-t. into the required unit (kPa) of Eq. IV.2., use the following factor:

PS (kPa) = PS (psi) x 6.8948

(Eq. IV.3.)

Note: Eq. IV.2. is taken from the AWWA Manual M45, however the Composite Soil Constrained Modulus (M_s) is replaced by the Modulus of Soil Reaction (E').
E' is the parameter historically used to characterize the soil stiffness of the backfill, independent of the interaction with the pipe deformation.
MS reflects the stiffness of the soil as a result of the interaction between the pipe deformation and the installation parameters (trench dimensions, native- and backfill soil parameters).
At moderate depths of fill the values of MS are close to the E'-values.
On request or for specific installations our engineers can supply calculations using MS.

Note: For depths of fill less than 0.5 m or for life load magnitudes greater than 89,000 N it may be necessary to consider the local life load effects. Such an analysis is beyond the scope of this Guide.

IV.3.1.1. Deflection lag factor

The deflection lag factor (D_L) converts the immediate deflection of the pipe to the deflection of the pipe after many years. For long term deflection prediction a DL-value greater than 1.00 is appropriate according the AWWA Manual M45. We advise to use a conservative value of DL= 1.25.

IV.3.1.2. Vertical soil load

The long term vertical soil load (WC) may be considered as the weight of the rectangular prism of soil directly above the pipe. The soil load is calculated according equation Eq. IV.4.

$$W_C = \Upsilon_S \times H$$

(Eq. IV.4.)

Where:
W_C = Vertical soil load (N/m^2)
Υ_S = Unit weight of soil above the pipe (N/m^3)
H = Burial depth to top of pipe. (m)

Note: In the absence of specific soil information the unit weight of soil may be assumed 18,800 N/m3.

IV.3.1.3. Live load

The following calculations may be used to compute the life load on the pipe for surface traffic.
The calculations consider a single-axle truck, travelling perpendicular to the pipe on an unpaved surface or a road with flexible pavement.

$$W_L = \frac{M_P \times P_W \times I_f}{L_1 \times L_2}$$

(Eq. IV.5.)

Where:
W_L = Life load on pipe (N/m^2)
M_P = Multiple presence factor (-)
P_W = Wheel load (see table IV-a.) (N)
If = Impact factor (see Eq. IV.6.) (-)
L_1 = Load width parallel to direction of travel (see Eq. IV.7.) (m)
L_2 = Load width perpendicular to direction of travel (see Eq. IV.8., IV.9., IV.10.) (m)

Note: M_P = Factor resulting in acceptably conservative load estimates.
M_P = 1.2 (-)

Table IV-a. Wheel load (Pw)

Identification	Wheel load (N)
VOSB 30	50,000
VOSB 45	75,000
VOSB 60	100,000
AASHTO HS-20	71,300
AASHTO HS-25	89,000
LKW 12	40,000
SKW 30	50,000
SKW 60	100,000

$$I_f = \frac{1+0.33\ [(2.44-H)}{2.44 \geq 1.0}$$

(Eq. IV.6.)

Where:
I_f = Impact factor (-)
H = Burial depth to top of pipe (m)

$$L_1 = t_l + LLDF \times H$$

(Eq. IV.7.)

Where:
L_1 = Load width parallel to direction of travel (m)
t_l = Length of tire footprint (m)
LLDF= Factor to account for life load distribution with depth of fill (-)
H = Burial depth to top of pipe. (m)

Note: t_l = 0.25 m
Note: LLDF = Factor depending on Soil Stiffness Category (SC); see table IV-c.

LLDF = 1.15 for SC1 and SC2
LLDF = 1.0 for all other backfills.

If:

$$H \leq H_{int}$$

(Eq. IV.8.)

Then:

$$L_2 = t_w + LLDF \times H$$

(Eq. IV.9.)

Else:

$$L_2 = \frac{(t_w + 1.83 + LLDF \times H)}{2}$$

(Eq. IV.10.)

Where:
H = Burial depth to top of pipe (m)
H_{int} = Depth at which load from wheels interacts (see Eq. IV.11.) (m)
L_2 = Load width perpendicular to direction of travel (m)
t_w = Width of tire footprint (m)
LLDF= Factor to account for life load distribution with depth of fill (see Eq. IV.7.). (-)

Note: t_w = 0.5 m

$$H_{int} = \frac{(1.83 - t_w)}{LLDF}$$

(Eq. IV.11.)

IV.3.1.3.1. Calculation notes

- Live load reduction ratio

The above calculation assumes that the life load (WL) extends over the full diameter of the pipe. This may be conservative for large diameter pipe under low fills, where L1 and L2 < OD.
To account for this, the calculated life load pressure on the pipe may be reduced by multiplying this life load pressure with a reduction ratio shown in table IV-b. The reduction ratio depends on the truck travel direction relative to the longitudinal axis of the buried pipe, as follows:

Table IV-b. Reduction ratio life load

Truck movement	Reduction ratio (m/m)
Across the pipe	L_1 / OD
Parallel to the pipe	L_2 / OD

- Tandem-axle correction

The previous calculation is valid for single-axis trucks. If both axles of a tandem-axle truck load the pipe at the same time, the load width parallel to the direction of travel (L1) should be substituted as shown in Eq. IV.12.

$$L_1 = \frac{(\text{axle spacing} + t_1 + LLDF \times H)}{2}$$

(Eq. IV.12.)

Table IV-c. Soil stiffness categories and Modulus of soil reaction

Soil Stiffness Category	Soil Types backfill material ♪	Modulus of soil reaction (E') for degree of compaction (MPa)			
		Dumped	Slight ♫	Moderate ♫	High ♫
SC1	Crushed rock: ≤15 % sand, maximum 25 % passing the 10 mm sieve and maximum 5 % passing No. 200 sieve.	6.9	20.7		
SC2	Clean, coarse-grained soils: SW, SP, GW, GP, or any soil beginning with one of these symbols with 12 % or less passing No. 200 sieve	1.4	6.9	13.8	20.7
SC3	Coarse-grained soils: GM, GC, SM, SC, or any soil beginning with one of these symbols with more than 12 % fines. Sandy or gravely fine grained soils: CL, ML (or CL-ML, CL/ML, ML/CL) with more than 30 % retained on a No. 200 sieve.	0.69	2.8	6.9	13.8
SC4	Fine-grained soils: CL, ML (or CL-ML, CL/ML, ML/CL) with 30 % or less retained on a No. 200 sieve.	0.34	1.4	2.8	6.9
SC5	Highly plastic and organic soils: MH, CH, OL, OH, PT.	Not suitable for use as backfill for flexible pipe			

♪ In line with ASTM D2487, Practice for classification of soils for engineering purposes; see table IV-d.
♫ Slight = < SPD85/ relative density < 40 %
Moderate = SPD85 < SPD95/ 40 %< relative density < 70%
High = > SPD95/ >70 % relative density.
SPD = Standard Proctor Density.

Table IV-d. Soil classification

Group Symbol♪	Group name
GW	Well graded gravels, gravel-sand mixtures, little or no fines
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
GM	Silt gravels, poorly graded gravel-sand-slit mixtures
GC	Clayey gravels, poorly graded gravel-sand-clay mixtures
SW	Well graded sands, gravely sands, little or no fines
SP	Poorly graded sands, gravely sands, little or no fines
SM	Silt sands, poorly graded sand-silt mixtures
SC	Clayey sands, poorly graded sand-clay mixtures
ML	Inorganic silts and very find sand, salty or clayey fine sands
CL	Inorganic clays of low to medium plasticity
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silt soils, elastic silts
CH	Inorganic clays of high plasticity, fat clays

♪ In line with ASTM D 2487.

IV.4. Resulting hoop stress

The maximum hoop stress resulting from the combined effects of internal pressure and deflection shall meet the following equation:

$$\frac{\sigma_c}{HDB} \leq \frac{1}{F_S}$$

(Eq. IV.13.)

Where:

σ_c = Resulting hoop stress (N/mm²)
HDB = Hydrostatic Design Basis (see table II-f.) (N/mm²)
F_S = Design factor (1.5) (-)

σ_c is calculated as follows:

$$\sigma_c = \frac{P \times D}{2 \times T_E} + D_f \times E_H \times R_c \times \left(\frac{\Delta_Y}{D}\right) \times \left(\frac{T_T}{D}\right)$$

(Eq. IV.14.)

Where:

σ_c = Resulting hoop stress (N/mm²)
P = Operating pressure (MPa)
D = Mean pipe diameter (mm)
T_E = Minimum reinforced wall thickness (see tables II-b. and II-c.) (mm)
D_f = Shape factor (see table IV-f.) (-)
E_H = Hoop bending modulus (see table II-g.) (N/mm²)
R_c = Re-rounding coefficient (see Eq. IV.15., IV.16., IV.17.) (-)
Δ_Y = Predicted vertical pipe deflection (see Eq. IV.2.) (mm)
T_T = Total wall thickness (mm)

Note: Δ_Y/D = Predicted vertical pipe deflection, fraction of mean diameter (%)
D = ID + 2 * TL + TE (see section II.5.A.).

Note: TT = $T_L + T_E$ (see section II.5.A.).

If:

P>3 MPa
(Eq. IV.15.)

Then:

$R_c=0$

(Eq. IV.16.)

Else:

$$R_c = 1 - \frac{P}{3}$$

(Eq. IV.17.)

Table IV-f. Shape factor

Pipe Stiffness (kPa)	Shape factor D_f (-)			
	Pipe-zone backfill material and compaction			
	Gravel		Sand	
	Dumped to slight	Moderate to high	Dumped to slight	Moderate to high
62	5.5	7.0	6.0	8.0
124	4.5	5.5	5.0	6.5
248	3.8	4.5	4.0	5.5
496	3.3	3.8	3.5	4.5

IV.5. Allowable combined stress

The combination of the axial stress due to internal pressure (SX) and the circumferential stresses due to internal pressure (SY) and vertical deflection of the pipe (σc), should not exceed the acceptable stress levels as shown in the fig. II-7.

The occurring axial stress has a great influence on the allowable hoop stress. Non-tensile resistant pipes (series ESN) allow for high hoop stress. It could be more beneficial to use this type of pipe for underground applications.

The occurring axial stress for tensile resistant and the non-tensile resistant pipes is calculated as follows:

A. Tensile resistant system (series EST)

$$S_X = \frac{1}{2} \times S_Y$$

(Eq. IV.18.)

Where:
S_X = Actual axial stress due to internal pressure (N/mm²)
S_Y = Actual hoop stress due to internal pressure (N/mm²)

$$S_Y = \frac{P}{2} \times \left(\frac{ID}{T_E} + 1\right)$$

(Eq. IV.19.)

Where:
P = Operating pressure (MPa)
ID = Inner diameter (mm)
TE = Minimum reinforced wall thickness (see tables II-b. and II-c.) (mm)

B. Non-tensile resistant system (series ESN)

$$S_X = N_{YX} \times S_Y$$

(Eq. IV.20.)

Where:
S_X = Actual axial stress due to internal pressure (N/mm²)
N_{YX} = Poisson ratio hoop/axial (see table II-g.) (-)
S_Y = Actual hoop stress due to internal pressure (see Eq. IV.19.) (N/mm²)

APPENDIX I: LIST OF SYMBOLS

Symbol	Explanation	Unit
A	= Structural wall area	(mm²)
A_B	= Bore area	(mm²)
C_J	= Conical/Cylindrical adhesive bonded Joint	
c	= Wave velocity	(m/s)
D	= Mean pipe diameter	(mm)
D_f	= Shape factor	(-)
DI	= Structural inner diameter	(mm)
DL	= Deflection lag factor	(-)
DO	= Structural outer diameter	(mm)
E'	= Modulus of soil reaction	(MPa)
E_H	= Hoop bending modulus	(N/mm²), (psi)
E_S	= Shear modulus	(N/mm²)
E_V	= Volumetric E-modulus	(N/mm²)
E_X	= Axial bending/tensile modulus	(N/mm²)
E_{XT}	= Axial bending/tensile modulus at elevated temperature	(N/mm²)
FJ	= Flange Joint	
F_S	= Design factor	(-)
F_W	= Frictional stress between soil and pipe	(N/mm²)
f	= Constant	(-)
G_B	= Linear mass of the pipe	(kg/m)
G_V	= Linear mass of the pipe content	(kg/m)
g	= Acceleration due to gravity	(m/s²)
H	= Burial depth to top of the pipe	(m)
H_{int}	= Depth at which load from wheels interacts	(m)
HDB	= Hydrostatic Design Basis	(N/mm²)
HDS	= Hydrostatic Design Stress	(N/mm²)
ID	= Inner diameter	(mm), (m), (in)
I_f	= Impact factor	(-)
I_R	= Radius of inertia	(mm)
I_Z	= Linear moment of inertia	(mm⁴)
K_V	= Compression modulus of the fluid	(N/mm²)
K_X	= Bedding coefficient	(-)
k	= Wall roughness	(mm)
L'	= Support distance at operating temperature (T) and –pressure (P)	(m)
L_A	= Fictive anchor length	(m)
L_C	= Continuous span length	(mm), (m)
L_{C1}	= Continuous span length based on the axial stress	(mm)
L_{C2}	= Continuous span length based on sag	(mm)
L_{EQ}	= Equivalent pipe length	(m)
L_F	= Final support distance	(m)

Symbol	Explanation	Unit
LJ	= Laminate Joint	
LLDF	= Factor to account for life load distribution with depth of fill	(-)
L_S	= Single span length	(mm), (m)
L_{S1}	= Single span length based on the axial stress	(mm)
L_{S2}	= Single span length based on sag	(mm)
L_1	= Load width parallel to direction of travel	(m)
L_2	= Load width perpendicular to direction of travel	(m)
MC	= Mechanical Coupler	
M_P	= Multiple presence factor	(-)
N_{XY}	= Poisson ratio axial/hoop	(-)
N_{YX}	= Poisson ratio hoop/axial	(-)
OD	= Outer diameter	(mm)
P	= Operating pressure	(MPa)
P_A	= Anchor load	(N)
P_{AT}	= Anchor load at elevated temperature	(N)
P_B	= Buckling pressure	(bar)
P_{BT}	= Buckling pressure at elevated temperature	(bar)
P_N	= Nominal pressure	(MPa)
PS	= Pipe Stiffness	(psi), (kPa)
P_W	= Wheel load	(N)
Q_P	= linear weight of the filled pipe	(N/mm)
RSJ	= Rubber Seal Joint	
RSLJ	= Rubber Seal Lock Joint	
R	= Ratio axial stress/hoop stress, Elbow radius	(-), (mm)
R_b	= Bending radius	(m)
R_c	= Re-rounding coefficient	(-)
R_E	= Temperature correction factor E-modulus	(-)
r_m	= Mean pipe radius	(mm), (in)
R_S	= Density correction factor	(-)
R_T	= Temperature change correction factor	(-)
S	= Specific Ring Stiffness	(N/m²)
S_A	= Remaining axial stress	(N/mm²)
S_b	= Load-dependent safety factor	(-)
S_{eq}	= Equivalent stress	(N/mm²)
$S_{eq(max)}$	= Maximum equivalent stress	(N/mm²)
SF	= Stiffness Factor	(in².lb/in)
S_F	= Service factor	(-)
S_f	= Service (design) factor	(-)
S_H	= Allowable hoop stress	(N/mm²)
S_L	= Density of the laminate	(kg/m³)
SPD	= Standard Proctor Density	(%)
S_V	= Density of the fluid	(kg/m³)

Symbol	Explanation	Unit
S_X	= Actual axial stress due to internal pressure	(N/mm^2)
S_{XT}	= Allowable axial stress	(N/mm^2)
S_Y	= Actual hoop stress due to internal pressure	(N/mm^2)
TJ	= Taper/Taper adhesive bonded Joint	
T	= Operating temperature	(°C)
TC	= Topcoat thickness	(mm)
T_E	= Minimum reinforced wall thickness	(mm), (m), (in)
T_L	= Liner thickness	(mm)
t_l	= Length of tire footprint	(m)
T_T	= Nett total wall thickness	(mm)
T_W	= Total wall thickness	(mm)
t_w	= Width of the tire footprint	(m)
UEWS	= Ultimate Elastic Wall Stress	(N/mm^2)
v	= Flow velocity	(m/s)
W_B	= Moment of resistance to bending	(mm^3)
W_C	= Vertical soil load	(N/m^2)
W_L	= Live load on pipe	(N/m^2)
W_W	= Moment of resistance to torsion	(mm3)
α	= Ageing and environment reduction factor E-modulus	(-)
$\Delta H_{fitting}$	= Head loss in the fitting	(N/m^2)
ΔH_{pipe}	= Head loss in the pipe	(m.h.w./m)
ΔP	= Pressure change	(m.h.w.)
ΔT	= Temperature change	(°C)
$\Delta Y/D$	= Predicted vertical pipe deflection, fraction of mean diameter	(%)
Δy	= Predicted vertical pipe deflection	(mm)
Δv	= Change in flow velocity	(m/s)
ΥS	= Unit weight of soil	(N/m^3)
ΥL	= Coefficient of linear thermal expansion	(mm/mm.°C)
σ_c	= Resulting hoop stress	(N/m^2)
ζ	= Friction coefficient	(-)
τ	= Shear stress	(N/mm^2)
ω	= Winding angle	(°)

APPENDIX II: CONVERSION TABLES

Conversion figures for Anglo-Saxon units into metric units

Length (SI = m)

1 inch		= 0.02540 m
1 foot	= 12 inch	= 0.30480 m
0.91 meter	= 3 ft	= 0.91440 m
1 mile	= 1760 yards	= 1.60935*103 m
1 sea mile		= 1.852*103 m

Area (SI = m^2)

1 square inch		= 6.4516*10-4 m^2
1 square foot	= 144 $inch^2$	= 9.2903*10-2 m^2
1 square yard	= 9 ft2	= 0.8361 m^2
1 acre	= 4840 $yards^2$	= 4,046.85 m^2
1 square mile	= 640 acres	= 2.58998*106 m^2
1 circular inch	= $\alpha/4$ $inch^2$	= 5.067107*10-4 m^2

Volume (SI = m^3)

1 cubic inch		= 16.3871*10-6 m^3
1 cubic foot	= 1728 $inch^3$	= 28.3168*10-3 m^3
1 cubic yard	= 27 ft3	= 0.764555 m^3
1 imperial gallon		= 4.54609*10-3 m^3
1 US gallon		= 3.78543*10-3 m^3
1 US barrel (petrol)		= 0.158762 m^3
1 barrel (imperial)		= 0.163656 m^3

Mass (SI = kg)

1 grain		= $0.0648*10^{-3}$ kg
1 ounce	= 437.5 grains	= 0.0283495 kg
1 pound	= 16 oz	= 0.4535924 kg
1 US long ton	= 2240 lb	= 1,016.05 kg
1 US short ton	= 2000 lb	= 907.185 kg
1 hundred weight (imp.)		= 50.80235 kg
1 hundred weight (US)		= 45.3592 kg

Mass per length (SI = kg/m)

1 pound/inch	= 17.858 kg/m
1 pound/foot	= 1.488 kg/m
1 pound/yard	= 0.4961 kg/m

Mass per area (SI = kg/m^2)

1 pound/inch2	= 0.0703*104 kg/m^2
1 pound/foot2	= 4.8825 kg/m^2
1 pound/yard2	= 0.5425 kg/m^2

Density (SI = kg/m^3)

1 grain/$foot^3$	= $2.288*10^{-3}$ kg/m^3
1 pound/$foot^3$	= 16.0256 kg/m^3
1 grain/gallon (US)	= 1.711 kg/m^3
1 pound/gallon (US)	= 119.8 kg/m^3

Pressure (SI = Pa = 1 N/m^2 = 10^{-5} bar)

1 pound/$inch^2$	= $6.89476*10^3$ N/m^2
1 pound/$foot^2$	= 4.7876 N/m^2
1 pound/$yard^2$	= 5.3201 N/m^2
1 long ton/$inch^2$ (imp.)	= $1.0725*10^5$ N/m^2
1 long ton/$foot^2$ (imp.)	= $1.5444*10^7$ N/m^2
1 short ton/$inch^2$ (US)	= $1.37894*10^7$ N/m^2
1 grain/$inch^2$	= $0.98497*10^2$ N/m^2
1 ounce/$inch^2$	= $4.3092*10^2$ N/m^2
1 ounce/$foot^2$	= 2.9925 N/m^2
1 ounce/$yard^2$	= 0.3313 N/m^2
1 inch head of water	= 249.089 N/m^2
1 inch head of mercury	= $3.38639*10^3$ N/m^2
1 foot head of water	= $2.98788*10^2$ N/m^2

Power (SI = W)

1 foot pounds/second	= 1.35582 W
1 foot pounds/minute	= $2.25*10^{-2}$ W
1 British thermal unit/second	= $1.05486*10^{-3}$ W
1 centigrade thermal unit/second	= $1.8987*10^{-3}$ W
1 horse power (Hp)	= $7.457*10^{-4}$ W

Work (SI = Nm = J)

1 foot pound	= 1.35582 J
1 yard pound	= 4.0674^6 J
1 foot ton (US)	= $2.7164*10^3$ J
1 foot ton (imp.)	= $3.0371*10^3$ J
1 Hp.hour	= $2.68145*10^6$ J
1 Btu	= $1.0555*10^3$ J
1 Ctu	= $1.8991*10^3$ J

Acceleration (SI = m/s2)

1 foot/$second^2$	= 0.3048 m/s^2

Flow rate

1 $foot^3$/hour	= 0.02679 m^3/h
1 gallon/minute	= 227.1 dm^3/h

Mass base

1 pounds/hour	= 0.01088 tons/day
MT/D	= 0.4536 kg/h

Force (SI = N)

1 pounds force	= 4.4482 N

Heat

1 Btu/pound	= 2.326 kJ/kg
1 Btu/hour	= 0.2931 W
1 Btu/hour.foot2.°F	= 5.678 W/m2.°C
1 Btu/pond.°F	= 4.187 kJ/kg.°C
1 Btu/hour.foot2	= 3.155 W/m2
1 Btu.foot/hour.foot2.°F	= 1.731 W/m.°C
1 foot2.hour.°F / Btu	= 0.1761 m2.°C/W

Moment of inertia (SI = m^4)

1 inch4	= 4.162*10-6 m4

Moment of bending (SI = Nm)

1 inch.pound	= 0.1130 Nm
1 foot.pound	= 1.356 Nm

Velocity (SI = m/s)

1 foot/second	= 0.3048 m/s
1 foot/minute	= 0.00508 m/s
1 mile/hour	= 0.44704 m/s

Conversion figures for metric into Anglo-Saxon units

Length

1 metre	= 1.094 yards
	= 3.281 feet
	= 39.37 inch
1 kilometre	= 0.621 statute mile
	= 0.540 nautical mile

Area

1 millimetre^2	= 15.51*10-4 inch^2
1 metre^2	= 1.196 yards^2
	= 10.764 ft^2
1 kilometre^2	= 0.38564 mile^2
	= 0.02471 acres

Volume

1 metre^3	= 61,023.4 inch^3
	= 35.3198 ft^3
	= 1.30934 yards^3
	= 220 imperial gallon
	= 264.2 US gallon
	= 6.290 US barrel
	= 6.286 imperial barrel

Mass

1 kilogram	= 15430 grains
	= 35.27 oz
	= 2.205 lb
1 metric ton	= 1.102 US short tons
	= 0.984 long ton

Mass per length

1 kilogram/metre	= 0.056 lb/in
	= 0.672 lb/ft
	= 2.016 lb/yard

Mass per area (specific pressure)

1 kilogram/metre^2	= 0.0014 psi
	= 0.2048 psf
	= 1.8433 lb/yard2

Density

1 kilogram/metre^3	= 0.0624 lb/ft3
	= 437 grain/ft3
	= 58.4 grain/gallon

Moment of inertia

millimetres^4	= 2.40269*10-6 inch4

Moment of bending

Newton.metre	= 8.850 inch.lb
	= 0.07375 ft.lb

Pressure

1 Newton/metre^2	= 0.0001450 psi
	= 0.0208873 psf
	= 0.18797 lb/yard^2
	= 0.01015 grains/in^2
	= 3.0184 oz/yard^2
	= 0.0023 oz/in^2
1 Mega Newton/metre2	= 9.324 lgtons/ft^2 (Eng)
	= 0.6475 lg tons/in^2 (Eng)
	= 0.725 srt tons/in^2 (US)

Power

1 kilowatt	= 738 ft.lb/s
	= 4.428*10^4 ft.lb/min
	= 0.94799 Btu/s
	= 0.526676 Ctu/s
	= 1.340536 Hp

Work

1 Joule	= 0.73756 ft.lb
	= 0.24585 yard.lb
	= 0.36813*10^{-3} ft.tons (US)
	= 0.32926*10^{-3} ft.tons (Eng)
	= 0.32501*10^{-6} Hp.h
	= 0.9474*10^{-3} Btu
	= 0.52657*10^{-3} Ctu

Heat

1 kilo Joule/kilo	= 0.42992 Btu/lb
1 Watt	= 0.341180 Btu/h
1 Watt/metre².°C	= 0.17612 Btu/h.ft².°F
1 Watt/metre²	= 0.316957 Btu/h.ft²
1 Watt/metre.°C	= 0.5777 Btu.ft/h.ft².°F
1 metre².°C/Watt	= 5.67859 ft².hr.°F/Btu
1 kilo Joule/kilo.°C	= 0.23883 Btu/lb.°F

Velocity

1 metre/second	= 3.28084 ft/s
	= 196.8504 ft/min
	= 2.236936 mile/h

Acceleration

1 metre/second2	= 3.28084 ft/s²

Flow rate

1 metre³/hour	= 37.32736 ft³/h
	= 4.40335 gallons/min

Mass base

1 MT/D	= 91.91176 lb/h
1 kilo/hour	= 2.20459 lb/h

Force

1 Newton	= 0.22481 lbf

Conversion figures for metric units into SI-units

Length (SI = m)

1 km	= 10³ m
1 cm	= 10⁻² m
1 mm	= 10⁻³ m
1 micron	= 10⁻⁶ m

Area (SI = m²)

1 km²	= 106 m²
1 cm²	= 10-4 m²
1 mm²	= 10-6 m²

Volume (SI = m³)

1 dm3	= 1 litre	= 10⁻³ m³
1 cm2		= 10-6 m³
1 mm3		= 10-9 m³

Mass (SI = kg)

1 milligram	= 10⁻⁶ kg
1 gram	= 10⁻³ kg
1 metric ton	= 10³ kg

Mass per length (SI = kg/m)

1 den	= (1/9)*10⁻⁶ kg/m
1 tex	= 10⁻⁶ kg/m

Mass per area

1 gram/mm2	= 10⁻³ kg/mm²
	= 10³ kg/m²

Density

1 gram/dm3	= 1 gram/ltr
	= 10⁻³ kg/dm³
	= 1 kg/m³

Pressure

1 bar	= 105 Pa	= 105 N/m²
1 kgf/cm2		= 9.8066 Pa
1 atm		= 101.325*10³ Pa
1 at		= 98066.5 Pa
1 Torr		= 133.322 Pa
1 metre head of water		= 9.80665*10³ Pa
1 metre head of mercury		= 133.322*10² Pa

Power

1 kgf.m/s	= 9.80665 W
1 metric horse power	= 735.499 W
1 kcal/hr	= 1.163 W

Work

1 Nm	= 1 J
1 kgf.m	= 9.80665 J
1 kWh	= 3.6*10⁶ J
1 kcal	= 4186.8 J
1 metric horse power hour	= 2.64780*10⁶ J
1 erg	= 1 dyn.cm = 10⁻⁷J

Acceleration

g	= gravitation	= 9.8067 m/s²

Velocity

1 km/h	= 0.2778 m/s
1 m/min	= 0.0167 m/s
1 knot	= 0.5144 m/s

Flow rate

1 litre/h	= 10⁻³ m³/h
1 m³/h	= 0.2778*10⁻³ m³/s

Mass base

1 kg/h		= 24.0 MT/D

Force

1 kgf		= 9.80665 N
1 dyn	= 1 g.cm/s^2	= 10-5 N

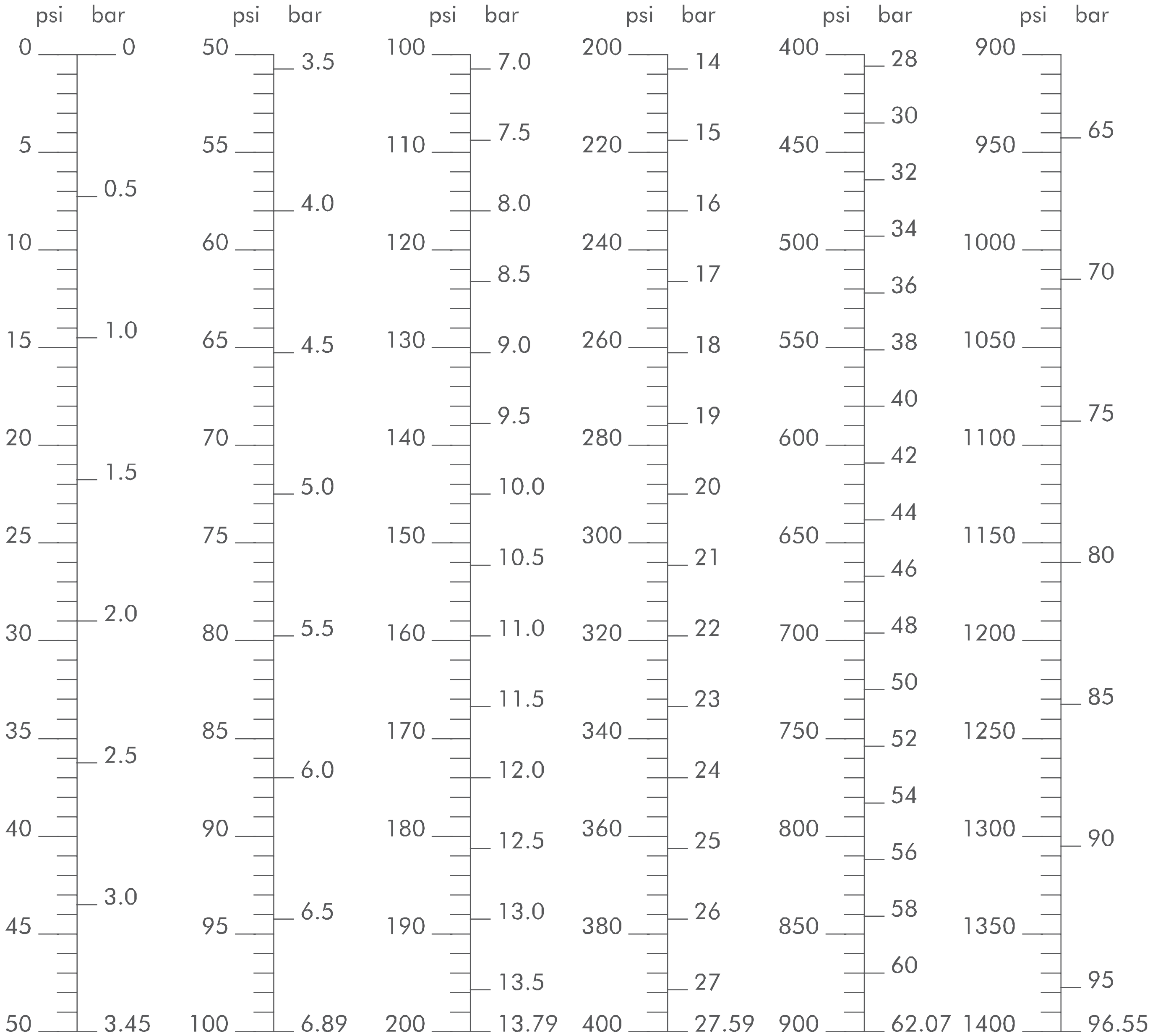
Heat

1 kcal/h	= 1.163 W
1 kcal	= 4186.8 J
1 kcal(h.m)	= 1.163 W/m
1 kcal(h.m^2)	= 1.163 W/m^2
1 cal(s.cm)	= 418.68 W/m

Prefixes

Prefix	Factor	Symbol
Giga	10^9	G
Mega	10^6	M
kilo	10^3	k
milli	10^{-3}	m
micro	10^{-6}	µ

APPENDIX III: CONVERSION GRAPH PSI VERSUS BAR



APPENDIX IV: CONVERSION GRAPH °C VERSUS °F