

WAVISTRONG

ENGINEERING GUIDE

FILAMENT WOUND EPOXY PIPELINE SYSTEMS
SERIES ES/EW/CS



FUTURE PIPE INDUSTRIES

Complete Pipe System Solutions

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I. Introduction

This Wavistrong Engineering Guide provides information for the design, specification and installation of Wavistrong glass fiber reinforced epoxy pipe systems. The pipe ranges from diameter 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 Theory¹.

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.

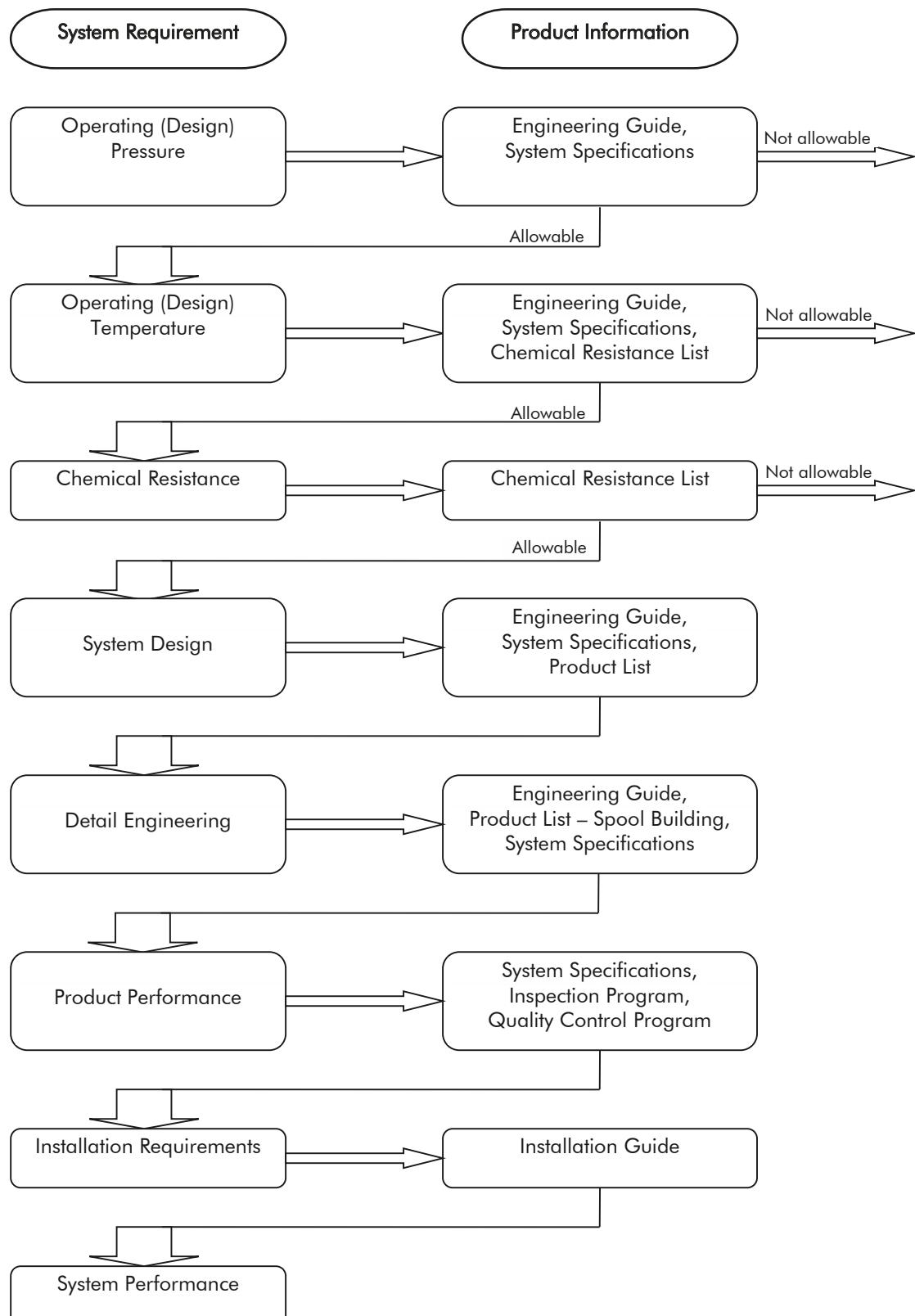
Besides the need for technical discussions many of these questions are answered in our technical literature.

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.

¹ „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



II. 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 110 °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 reinforced 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. |
| 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 (S_f) of 0.5; this implies a long term safety factor of 2.

Example: Wavistrong Series **EST 20** means: **E**pox_y 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.

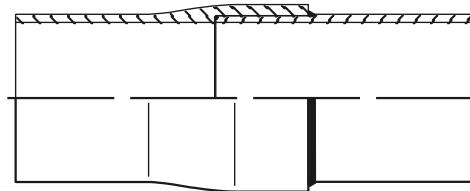
B. Non-tensile resistant type of joints

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.

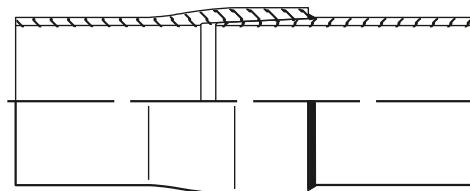


Symbol: 

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.



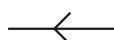
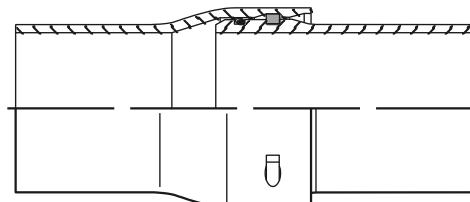
Symbol: 

Fig. II.2. TJ

C. Rubber seal lock joint (RSLJ)

This type of joint consists of an integral filament wound socket end and a machined spigot end. The 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.).



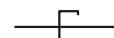
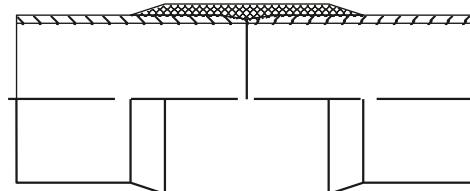
Symbol: 

Fig. II.3. RSLJ

D. Laminate joint (LJ)

Generally, this type of joint is only used on diameters over 400 mm (see fig. II.4.). The preparation of this rigid joint requires good craftsmanship; it is recommended that Future Pipe Industries provides the training and assistance during installation.



Symbol: 

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.).

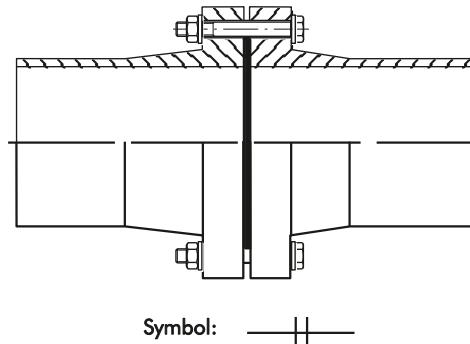


Fig. II.5. FJ

II.4.2. Non-tensile resistant joints

A. Rubber seal joint (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 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.).

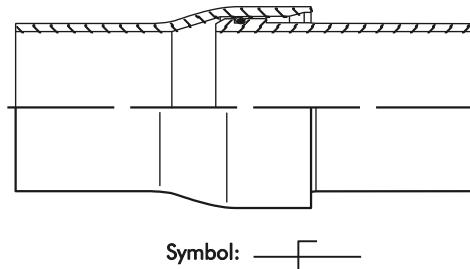


Fig. II.6. RSJ

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:

$$T_E = \frac{ID}{\frac{2 * S_H}{P_N} - 1} \quad (\text{Eq. II.1.})$$

Where:

T_E	= Minimum reinforced wall thickness	(mm)
ID	= Inner diameter	(mm)
S_H	= Allowable hoop stress (= HDS, see table II-f.)	(N/mm ²)
P_N	= Nominal pressure	(MPa)

Note: T_W = 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:

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

Where:

G_B	= Linear mass of the pipe	(kg/m)
OD	= Outer diameter	(mm)
ID	= Inner diameter	(mm)
S_L	= Specific gravity of the laminate (see table II-j.)	(kg/m ³)

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:

$$A = \frac{\pi}{4} * (DO^2 - DI^2) \quad (\text{Eq. II.3.})$$

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:

$$I_Z = \frac{\pi}{64} * (DO^4 - DI^4) \quad (\text{Eq. II.4.})$$

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:

$$I_R = \sqrt{\frac{I_Z}{A}} \quad (\text{Eq. II.5.})$$

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:

$$A_B = \frac{\pi}{4} * ID^2 \quad (\text{Eq. II.6.})$$

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:

$$W_B = \frac{\pi}{32} * \frac{DO^4 - DI^4}{DO} \quad (\text{Eq. II.7.})$$

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:

$$G_V = \frac{\pi}{4} * ID^2 * S_V * 10^{-6} \quad (\text{Eq. II.8.})$$

Where:

G_V = Linear mass of the pipe content (kg/m)

ID = Inner diameter (mm)

S_V = Specific gravity of the fluid (kg/m^3)

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

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 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
	1100	8.9	62.6	310.3	477891.6	392.4	9503.3	8542.9
	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
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
	1100	11.1	76.9	387.8	599594.5	393.2	9503.3	10676.5
	1200	12.1	90.9	461.1	848356.3	428.9	11309.7	13848.5
	1400	14.1	122.5	626.8	1569218.8	500.3	15393.8	21959.4
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
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

Table II-b-2. Pipe data for series EST (continued)

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 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
	80	2.4	1.5	6.3	54.7	29.5	50.3	12.8
EST 32	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
	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
EST 40	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
	25	1.8	0.4	1.6	1.5	9.8	4.9	1.0
EST 50	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 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)
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
	1100	8.0	56.7	278.7	428516.1	392.1	9503.3	7672.6
	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
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)	Specific gravity of the fluid S_v (kg/m ³)						
	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
1100	760.3	950.3	1140.4	1330.5	1520.5	1710.6	1900.7
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 (T_E) for fittings is also calculated with the use of the ISO-equation (see Eq. II.1.). However, the allowable hoop stress (S_H) is related to the fitting type.

For fittings ¹ the following allowable hoop stress is used:

- Elbow/Coupler $S_H = 40 \text{ N/mm}^2$
- Tee/Lateral/Reducer $S_H = 32 \text{ N/mm}^2$

¹ 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.

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	900-1200	1400
8									1 3	2 3	3	3	3	3
10										4	4	4	4	4
12.5								1 3	1 2 3	2 3	3	3	3	(5)
16							1 3	1 2 3 4	1 2 3 4	2 3 4	3 4			
20						1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	2 3 4	3			
25				1 2 3	1	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	2 3 4				
32	1 2 3 4	1	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	2					
40	1	2		2	2		2	2	2	2				
50	1 2	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
- FJ Flange Joint
- Available for all Inner Diameter/Pressure Class combinations



= See higher pressure class

Other joining systems are available on request.

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° .

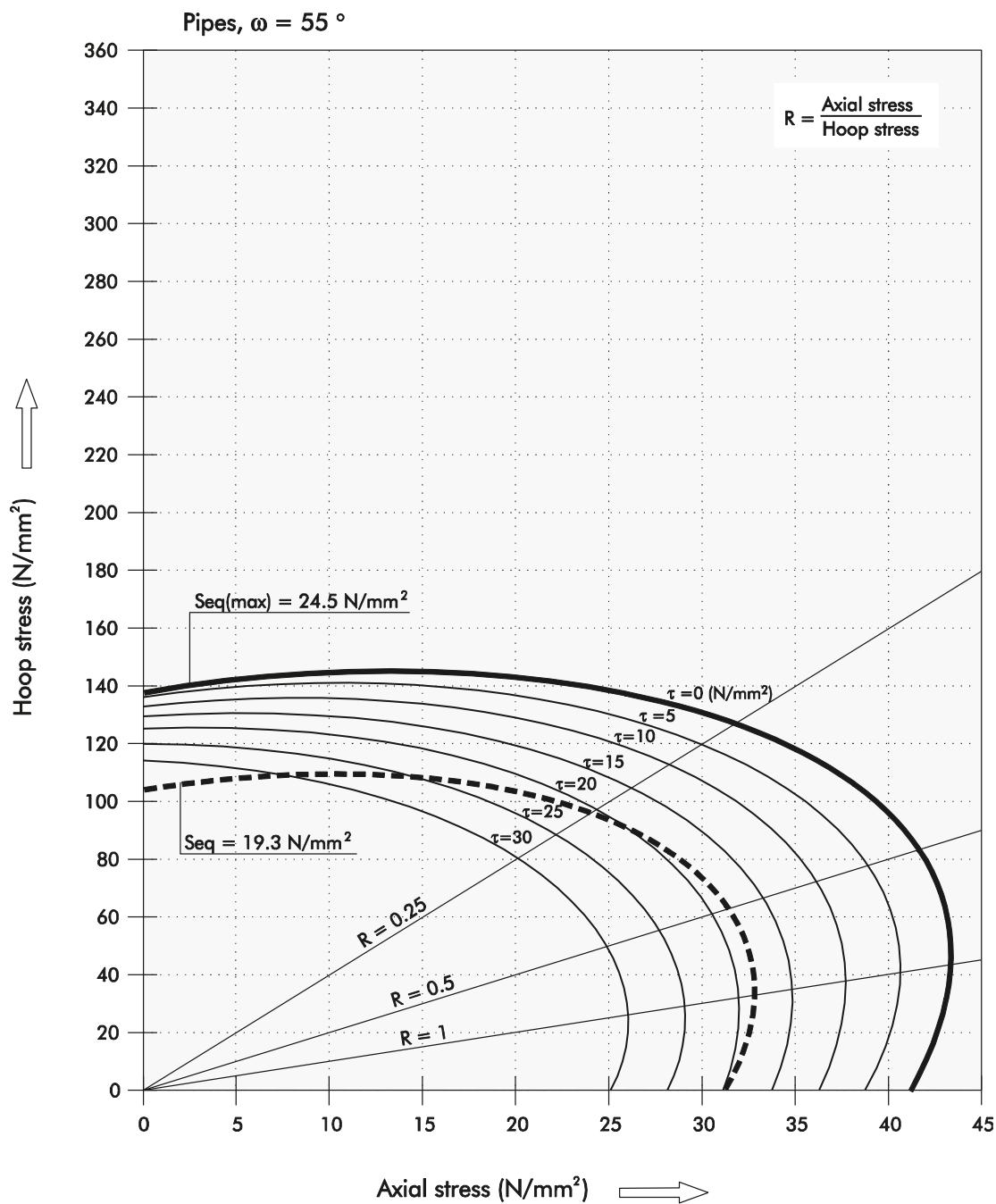
The equivalent stress (S_{eq}), is calculated with the Continuum Theory (see section I.) at bi-axial Hydrostatic Design Stress (HDS) level of the pipe and the use of a service (design) factor (S_f) = 0.5.

For this load situation $S_{eq} = 19.3 \text{ N/mm}^2$.

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

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

Fig. II.7-a. Pipes, winding angle $\omega = 55^\circ$



— — — Allowable stresses for hydrostatic loading; service (design) factor $S_i = 0.5$, $S_{eq} = 19.3 N/mm^2$.

— Allowable stresses for combined loading; service (design) factor $S_i = 0.67$, $S_{eq(max)} = 24.5 N/mm^2$.

— — — Allowable stresses for combined loading in combination with shear stress (τ), $S_{eq(max)} = 24.5 N/mm^2$.

Fig. II.7-b. Pipes, winding angle $\omega = 63^\circ$

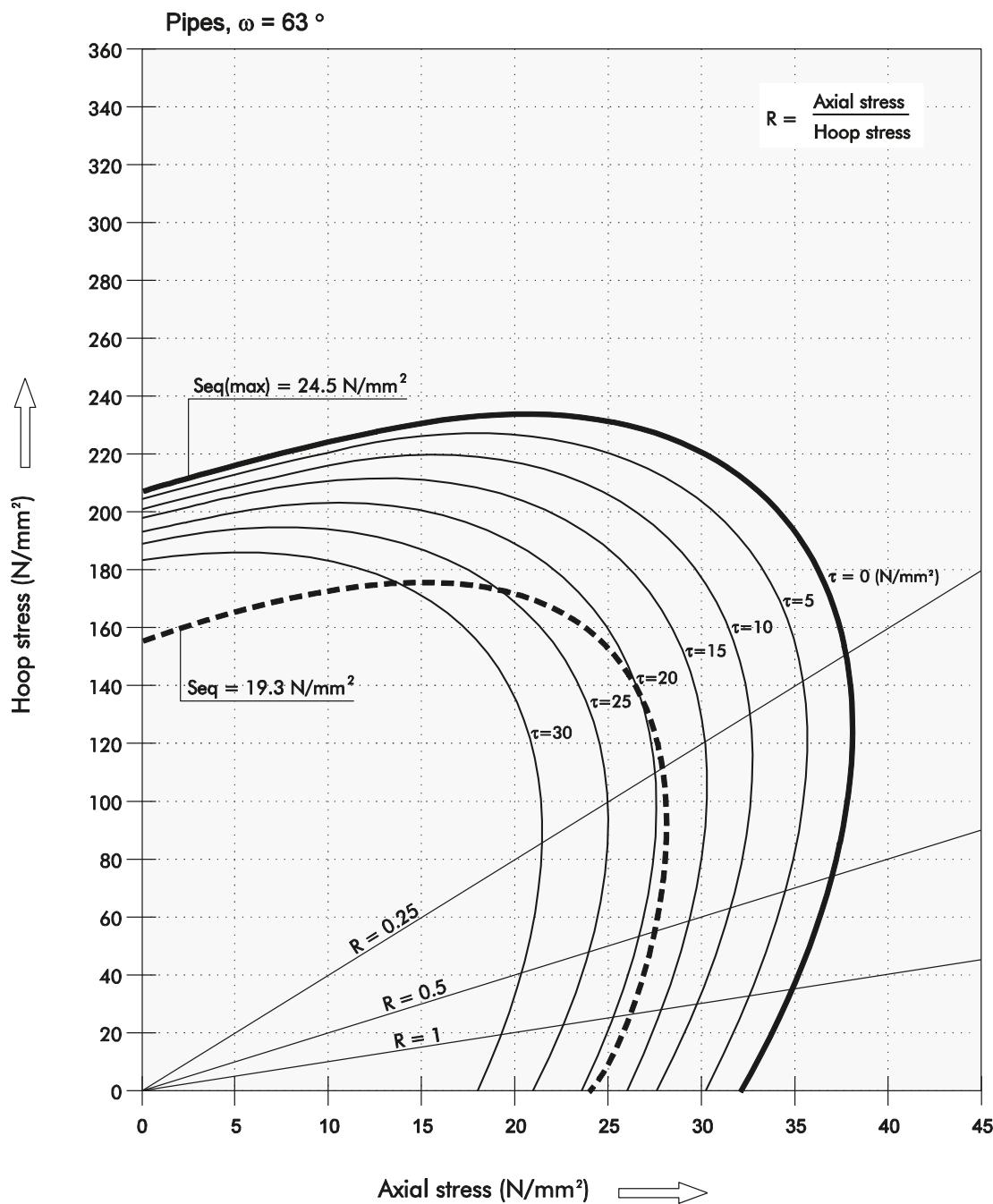
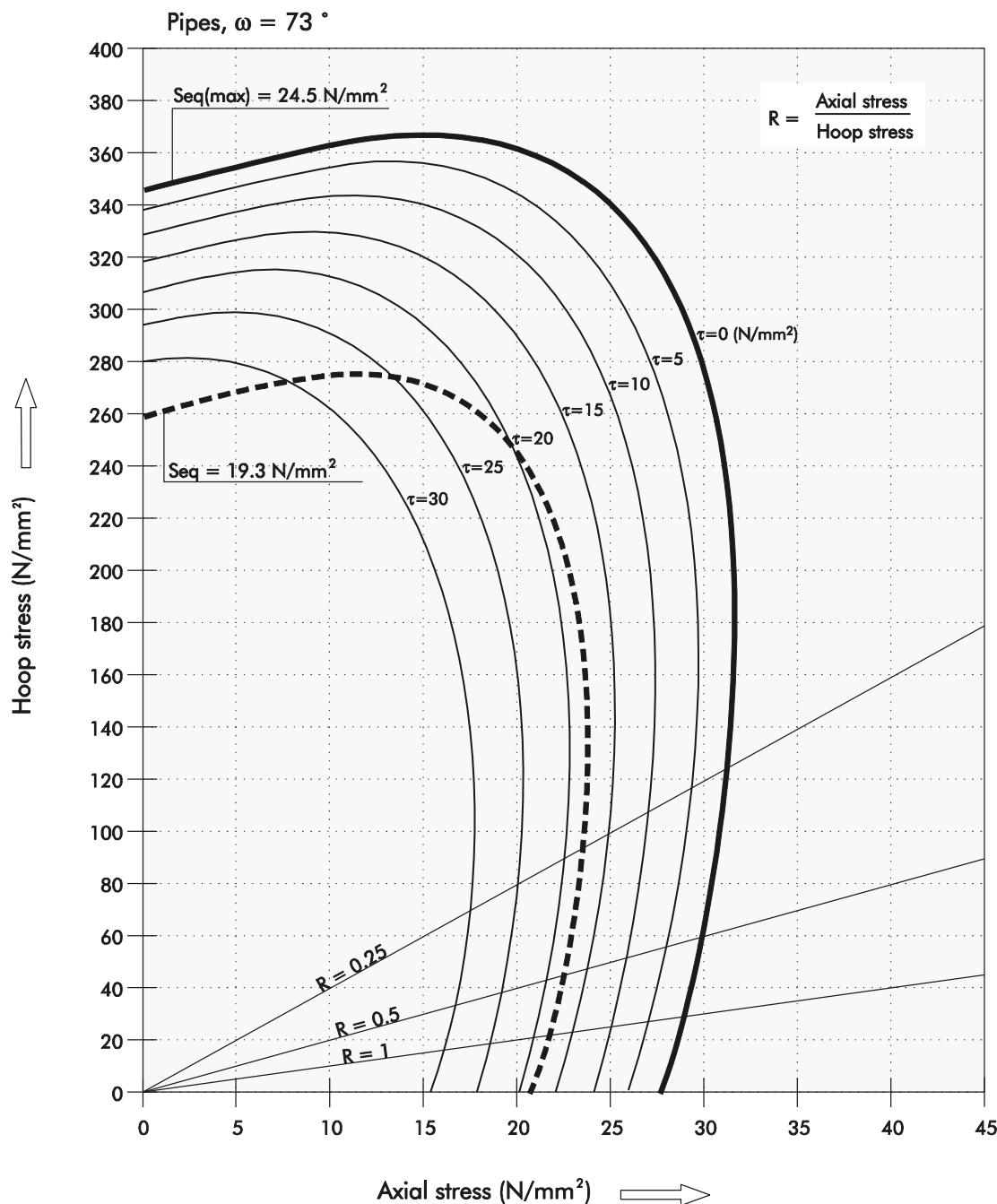


Fig. II.7-c. Pipes, winding angle $\omega = 73^\circ$



— — — Allowable stresses for hydrostatic loading; service (design) factor $S_i = 0.5$, $S_{eq} = 19.3 \text{ N/mm}^2$.

— — — Allowable stresses for combined loading; service (design) factor $S_i = 0.67$, $S_{eq(\max)} = 24.5 \text{ N/mm}^2$.

— — — Allowable stresses for combined loading in combination with shear stress (τ), $S_{eq(\max)} = 24.5 \text{ N/mm}^2$.

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 20 °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 D 1599	250	200		N/mm ²
Ultimate Elastic Wall Stress (UEWS)	Future Pipe Industries	160	140		N/mm ²
Hydrostatic Design Basis HDB (50 years)	ASTM D 2992 B	150	100		N/mm ²
Hydrostatic Design Stress HDS (50 years)	ASTM D 2992 B	63	50		N/mm²
Uni-axial loading: (R= 0.25)					
Ultimate hoop stress (Weeping)	ASTM D 1599		450	370	N/mm ²
Hydrostatic Design Basis HDB (50 years)	ASTM D 2992 B		200	160	N/mm ²
Hydrostatic Design Stress HDS (50 years)	ASTM D 2992 B		100	80	N/mm²

Note: HDS = HDB * S_f

Where:

HDS = Hydrostatic Design Stress

HDB = Hydrostatic Design Basis

S_f = Service (design) factor

S_f = Maximal 0.5

Table II-g. Mechanical properties

Property	Symbol	Test method	Winding angle (ω)			Unit
			55 °	63 °	73 °	
Axial tensile stress			65	55	40	N/mm ²
Axial tensile modulus		ASTM D 2105	10,500	10,000	10,000	N/mm ²
Hoop tensile stress		ASTM D 2290	210	260	400	N/mm ²
Hoop tensile modulus		ASTM D 2290	20,500	27,500	37,000	N/mm ²
Shear modulus	E_s		11,500	9,500	7,000	N/mm ²
Axial bending stress			80	65	50	N/mm ²
Axial bending modulus	E_x	ASTM D 2925	10,500	10,000	10,000	N/mm ²
Hoop bending stress		ASTM D 2412	90	120	160	N/mm ²
Hoop bending modulus	E_h	ASTM D 2412	20,500	27,500	37,000	N/mm ²
Poisson ratio axial/hoop ↴	N_{XY}		0.65	0.62	0.47	-
Poisson ratio hoop/axial ↴	N_{YX}		0.33	0.26	0.15	-

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

Correction factor R_E (-)		Winding angle (ω)	Temperature (°C)					
			20	40	60	80	100	110
R_{E1}		55 °	1	0.93	0.87	0.80	0.72	0.68
		63 °	1	0.93	0.87	0.80	0.72	0.68
		73 °	1	0.93	0.87	0.80	0.72	0.68
	R_{E4}	55 °	1	0.95	0.90	0.83	0.75	0.70
		63 °	1	0.97	0.94	0.90	0.85	0.82
		73 °	1	0.99	0.98	0.97	0.95	0.94

Table II-j. Physical properties

Property	Symbol	Test method	Unit	
Coefficient of linear thermal expansion			$2 * 10^{-5}$	mm/mm.°C
Thermal conductivity			0.29	W/m.K
Specific heat			921	J/kg.K
Glass content (by mass)			70 ± 5	%
Glass content (by volume)			52 ± 7	%
Specific gravity of the laminate			1850	kg/m ³
Barcol hardness			35	-
Surface resistance (Series C..)			$< 10 * 10^6$	Ω/m

↴ 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:

$$\Delta H_{fitting} = \zeta * \frac{l}{2} * S_V * v^2 \quad (\text{Eq. II.9.})$$

Where:

$\Delta H_{fitting}$	= Head loss in the fitting	(N/m ²)
ζ	= Friction coefficient	(-)
S_V	= Specific gravity of the 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 (L_{EQ}) when using the head loss in pipes from fig. II.8. and II.9.

$$L_{EQ} = \frac{\Delta H_{fitting}}{\Delta H_{pipe} * g * 1000} \quad (\text{Eq. II.10.})$$

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 ° 45 ° 90 °	0.11 0.16	0.07 0.24	0.30

Note: Elbows ID \geq 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	
$\frac{\Phi d}{\Phi}$	$\frac{d}{D}$	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 300 mm

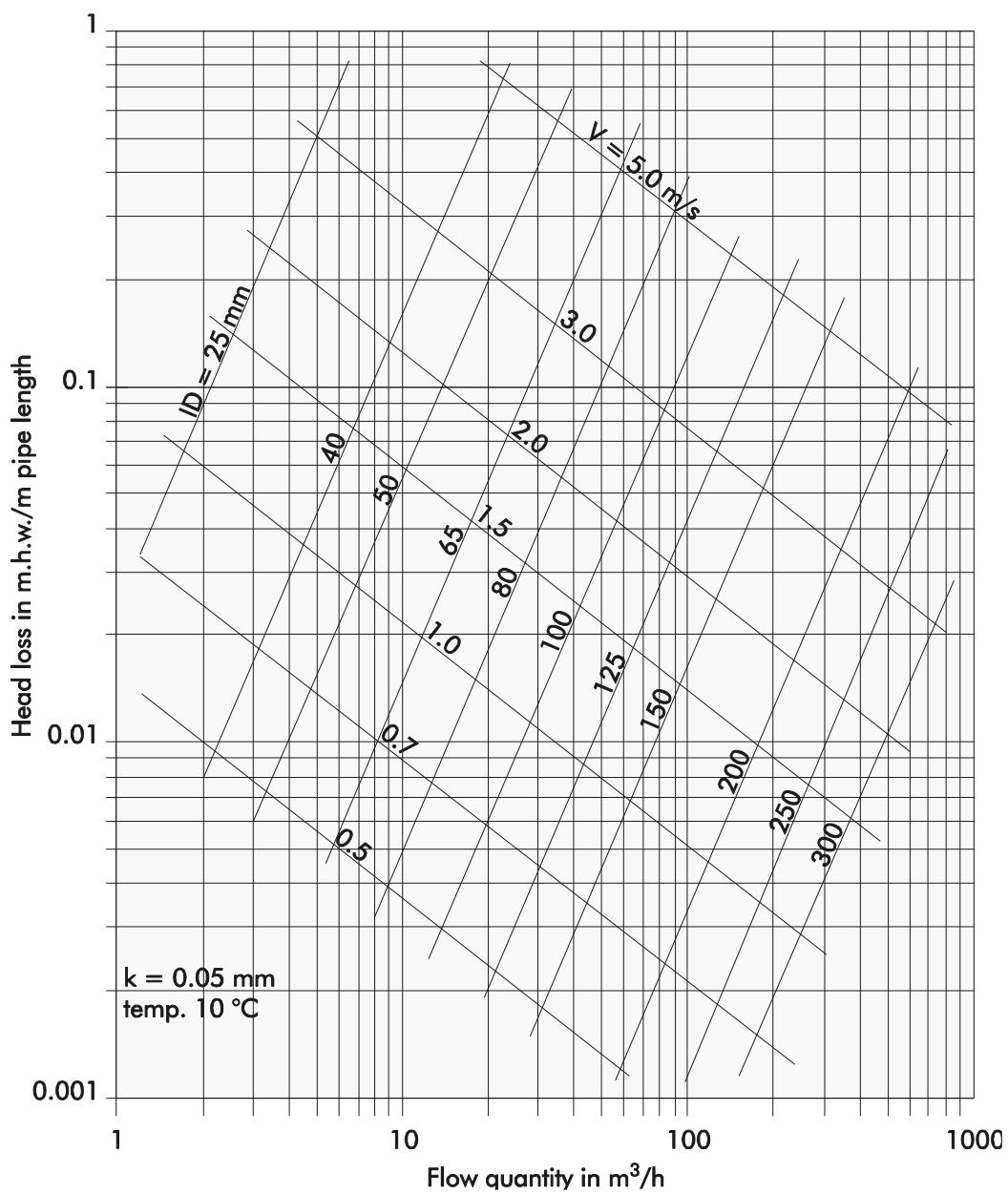
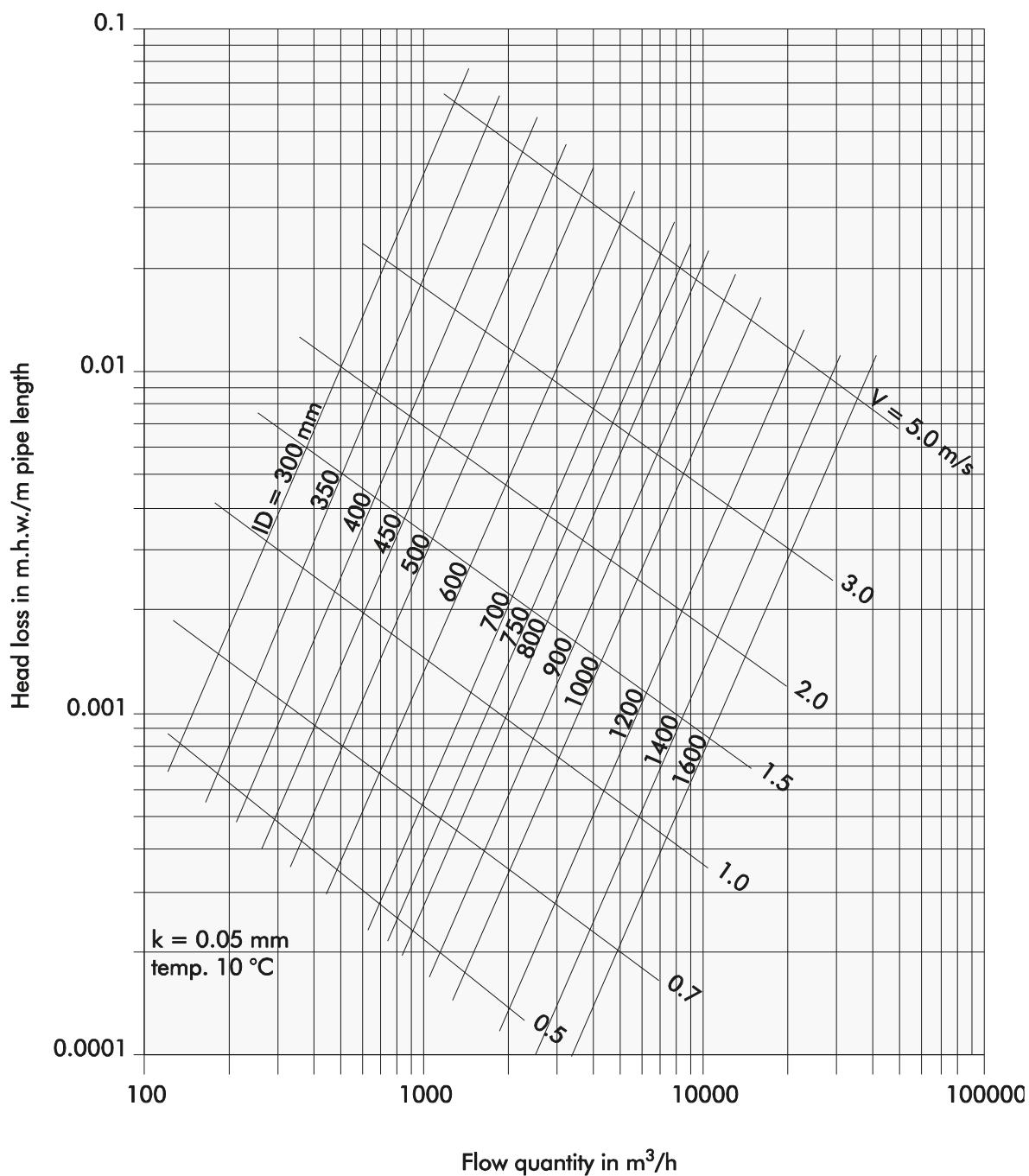


Fig. II.9. Head loss flow chart ID 300 mm through 1600 mm



II.8. Bending radius

The minimum allowable bending radius (R_b) for a pipe, installed at 20 °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:

$$R_b = \frac{0.0005 * R_E * E_X * DI}{S_A} \quad (\text{Eq. II.11.})$$

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/mm ²)
DI	= Structural inner diameter (see section II.5.1.C.)	(mm)
S_A	= Remaining axial stress	(N/mm ²)

The value of S_A is defined as follows:

$$S_A = S_{XT} - S_X \quad (\text{Eq. II.12.})$$

Where:

S_A	= Remaining axial stress	(N/mm ²)
S_{XT}	= Allowable axial stress	(N/mm ²)
S_X	= Actual axial stress due to internal pressure	(N/mm ²)

For bi-axial loaded systems:

$$S_X = \frac{P}{4} * \left(\frac{ID}{T_E} + 1 \right) \quad (\text{Eq. II.13.})$$

For uni-axial loaded systems:

$$S_X = \frac{P}{8} * \left(\frac{ID}{T_E} + 1 \right) \quad (\text{Eq. II.14.})$$

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 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 S_{XT} (N/mm²)

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 20 °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
	1100	777	456	323	250	204	172
	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
	1100	663	386	272	210	171	145
	1200	725	422	297	229	187	158
	1400	849	493	347	268	218	184
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
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

Table II-n-2. Bending radius R_b (m) at 20 °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 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
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 R_b (m) at 20 °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
	1100	716	494	377	305	256	220
	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
	200	92	66	52	43	36	31
ESN 20	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
	200	150	86	60	46	37	31
ESN 25	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
	80	22	19	17	15	14	13
ESN 32	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 Joukowsky⁵:

$$\Delta P = \frac{c}{g} * \Delta v \quad (\text{Eq. II.15.})$$

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:

$$c = \frac{1000}{\sqrt{S_V * \left(\frac{1}{K_V} + \frac{ID}{T_E * E_V} * f \right)}} \quad (\text{Eq. II.16.})$$

Where:

c	= Wave velocity	(m/s)
S_V	= Specific gravity of the fluid	(kg/m ³)
K_V	= Compression modulus of the fluid	(N/mm ²)
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.)	(-)

⁵ 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.

For an-isotropic materials, where the material characteristics are dependent on the winding angle (ω), the volumetric E-modulus (E_V) is calculated from the following equation:

$$E_V = \frac{\sqrt[3]{E_X * E_H^2}}{1 - N_{XY} * N_{YX}} \quad (\text{Eq. II.17.})$$

Where:

E_V	= Volumetric E-modulus	(N/mm ²)
E_X	= Axial bending modulus (see table II-g.)	(N/mm ²)
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.)	(-)

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

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

Winding angle (ω)	55 °	63 °	73 °
E_V	20,880	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.

$$f1 = \frac{5}{4} - 0.5 * N_{XY} * N_{YX} \quad (\text{Eq. II.18.})$$

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

$$f2 = 1 - N_{XY} * N_{YX} \quad (\text{Eq. II.19.})$$

- 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.

$$f3 = 1 - 0.5 * N_{YX} \quad (\text{Eq. II.20.})$$

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	1.14275	1.1694	-
f2	0.7855	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
	1100	387	451
	1200	387	451
	1400	387	450
EST 12.5	250	410	485
	300	410	485
	350	410	485
	400	410	485
	450	410	485
	500	413	489
	600	413	489
	700	412	488
	750	412	488
	800	412	488
	900	412	487
	1000	411	487
	1100	411	487
	1200	411	487
	1400	411	487
EST 16	200	453	535
	250	458	540
	300	456	538
	350	454	536
	400	457	539
	450	456	538
	500	455	537
	600	456	538
	700	457	539
	750	456	538
EST 20	800	455	537
	150	506	593
	200	513	601
	250	511	600
	300	510	599
	350	510	598
	400	509	597
	450	509	597
	500	509	597
	600	510	599

Series	ID (mm)	c1 (m/s)	c2 (m/s)
EST 25	100	601	698
	125	566	660
	150	565	658
	200	563	656
	250	562	655
	300	561	654
	350	560	653
	400	563	656
	450	562	655
	500	562	655
	600	561	654
EST 32	80	658	758
	100	621	719
	125	617	715
	150	615	712
	200	616	714
	250	617	715
	300	618	715
	350	618	716
	400	619	716
EST 40	50	706	808
	65	712	815
	80	679	780
	100	683	784
	125	681	782
	150	685	787
	200	683	784
	250	684	785
	300	683	784
	350	684	785
EST 50	400	683	784
	25	895	995
	40	766	869
	50	747	850
	65	744	847
	80	742	745
	100	747	850
	125	745	848
	150	747	850
	200	744	847

↳ Values of table II-r. are valid for the following conditions:

$$K_v = 2050 \text{ N/mm}^2$$

$$S_v = 1000 \text{ kg/m}^3$$

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
	1100	428	429
	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
ESN 32	80	771	761
	100	710	701
	125	652	642
	150	605	596
	200	613	604
	250	612	602
	300	611	601

↳ Values of table II-s. are valid for the following conditions:

$$K_V = 2050 \text{ N/mm}^2$$

$$S_V = 1000 \text{ kg/m}^3$$

II.10. Stiffness

An investigation of standards concerning the stiffness¹ 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 1115 and is calculated with the following formula:

$$S = \frac{1}{12} * E_H * \left(\frac{T_E}{ID + T_E} \right)^3 \quad (\text{Eq. II.21.})$$

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:

$$PS = 4.474 * E_H * \left(\frac{T_E}{ID + T_E} \right)^3 \quad (\text{Eq. II.22.})$$

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:

$$PS = 0.007787 * S \quad (\text{Eq. II.23.})$$

Where:

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

¹ 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.

$$SF = \frac{1}{12} * E_H * T_E^3 \quad (\text{Eq. II.24.})$$

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:

$$SF = 8.848 * (ID + T_E)^3 * S \quad (\text{Eq. II.25.})$$

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):

$$SF = 0.149 * r_m^3 * PS \quad (\text{Eq. II.26.})$$

Where:

SF	= Stiffness Factor	(in ² .lb/in)
r _m	= Mean pipe radius	(in)
PS	= Pipe Stiffness (see Eq. II.22.)	(psi)

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

Tables II-t. and II-u. show the values of the stiffness of the standard Wavistrong pipes according to various stiffness identifications at 20 °C.

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

Table II-t. Stiffness for series EST at 20 °C

Series EST				
Series	ID (mm)	S (N/m ²)	PS (psi)	SF (in ² .lb/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
	1100	1200	9	14250
	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
	1100	1700	13	20600
EST 16	1200	1700	13	26800
	1400	1700	13	42300
EST 20	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/m ²)	PS (psi)	SF (in ² .lb/in)
EST 25	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
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 20 °C

Series ESN				
Series	ID (mm)	S (N/m ²)	PS (psi)	SF (in ² .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
	1100	1150	9	13900
	1200	1100	9	17400
	1400	1100	9	27300
	350	1150	9	450
ESN 16	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
	200	3800	30	300
ESN 20	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
	200	4300	34	300
ESN 25	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
	80	56500	450	300
ESN 32	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) ¹ 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 20 °C and are calculated in accordance with equation Eq. II.27. ^{2,3} (pipe without stiff ends) using a safety factor $S_b = 1$.

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 (S_b) has to be taken into account.

Depending on the pipe installation and service conditions a safety factor $S_b > 1$ 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.

¹ Buckling pressure (P_B) = External Pressure (P_E) – Internal Pressure (P_i).
Full vacuum means: $P_E - P_i = 1$ bar.

^{2,3} Roark/Young, Formulas for stress and strain, McGraw-Hill, fifth edition.

Buckling Pressure (P_B), pipe without stiff ends:

$$P_B = \frac{S_F}{S_b} * 2.5 * \frac{E_H}{1 - N_{XY} * N_{YX}} * \left(\frac{T_E}{r_m} \right)^3 \quad (\text{Eq. II.27.})$$

Where:

P_B	= Buckling pressure	(bar)
S_F	= Service factor ($S_F = 0.75$)	(-)
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: $r_m = 0.5 * (\text{ID} + 2 * T_L + T_E)$

For the determination of buckling pressure at temperatures exceeding 20 °C, the temperature correction factors for the hoop bending modulus of elasticity (R_E) shall be applied (see table II-h.). Buckling pressure at elevated temperature (P_{BT}) is calculated with the aid of Eq. II.28.

$$P_{BT} = P_B * R_E \quad (\text{Eq. II.28.})$$

Where:

P_{BT}	= Buckling pressure at elevated temperature	(bar)
P_B	= Buckling pressure at 20 °C (see tables II-v. and II-w.)	(bar)
R_E	= Temperature correction factor (R_{E4}, R_{E5}, R_{E6}) for E-modulus (see table II-h.)	(-)

Table II-v. Ultimate buckling pressure P_B (bar) series EST at 20 °C and $S_B = 1$

ID (mm)	Pressure class (bar)							
	8	12.5	16	20	25	32	40	50
25								106.3
40								29.1
50							15.5	24.2
65							16.9	23.8
80						9.3	11.8	23.5
100					4.9	6.2	12.4	24.9
125					3.2	5.9	12.3	24.4
150				1.5	3.2	5.8	12.9	25.1
200			0.7	1.6	3.1	5.9	12.6	24.4
250		0.4	0.8	1.6	3.1	6.0	12.8	24.7
300		0.4	0.8	1.6	3.1	6.1	12.6	24.8
350	0.2	0.4	0.7	1.6	3.1	6.1	12.8	24.9
400	0.2	0.4	0.8	1.6	3.2	6.1	12.7	25.0
450	0.2	0.4	0.8	1.6	3.1			
500	0.2	0.4	0.7	1.6	3.1			
600	0.2	0.4	0.8	1.6	3.1			
700	0.2	0.4	0.8	1.6	3.1			
750	0.2	0.4	0.8	1.6				
800	0.3	0.4	0.8	1.6				
900	0.3	0.4						
1000	0.3	0.4						
1100	0.3	0.4						
1200	0.3	0.4						
1400	0.3	0.4						

Table II-w. Ultimate buckling pressure P_B (bar) series ESN at 20 °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				
1100	0.2				
1200	0.2				
1400	0.2				

II.12. Classification

The standard Wavistrong pipes can be classified in accordance with ASTM D 2310, indicating type, grade and Hydrostatic Design Basis (HDB).

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

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.

Table II-x. Designation code

	Series												
	EST	ESN	EST	EST	ESN	EST	ESN	EST	ESN	EST	ESN	EST	
P _N (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	-2111
40												-2111	-2111
50												-2111	-2111
65												-2112	-2112
80												-2112	-2112
100												-2112	-2113
125												-2112	-2115
150												-2112	-2114
200												-2112	-2116
250												-2112	-2115
300												-2112	-2116
350	-1112			-2112	-2112		-2113	-5112	-2112	-2112	-5112	-2116	-2116
400	-1112			-2112	-2115	-5112	-2116	-5113	-2115	-5112	-2116	-5113	-2116
450	-1112			-2113	-2116	-5112	-2116	-5114	-2116	-5113	-2116	-5115	-2116
500	-1113			-2115	-2116	-5113	-2116	-5112	-2116	-5114	-2116	-5115	-2116
600	-1115	-4015		-2116	-2116	-5115	-2116	-5116	-2116	-5116	-2116		-2116
700	-1116	-4016		-2116	-2116	-5116	-2116	-5116	-2116	-5116	-2116		-2116
750	-1116	-4016		-2116	-2116	-5116	-2116	-5116	-2116	-5116	-2116		-2116
800	-1116	-4016		-2116	-2116	-5116	-2116	-5116	-2116	-5116	-2116		-2116
900	-1116	-4016		-2116	-2116	-5116	-2116	-5116	-2116	-5116	-2116		-2116
1000	-1116	-4016		-2116	-2116	-5116	-2116	-5116	-2116	-5116	-2116		-2116
1100	-1116	-4016		-2116									
1200	-1116	-4016		-2116									
1400	-1116	-4016		-2116									

III. 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.).

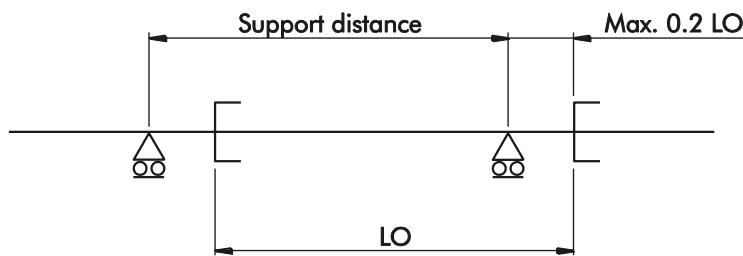


Fig. III.1. Support next to the joint

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.

Guides enabling the pipe system to move freely in longitudinal direction of the pipe must have a low friction sliding base to allow for this movement and a protective layer of PTFE, PE or equivalent.

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

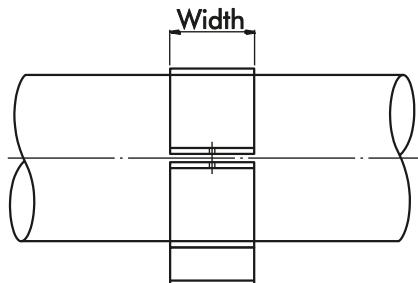


Fig. III.2.a. Single clamp

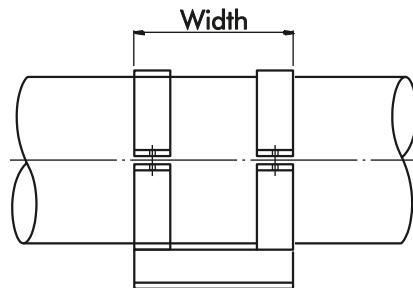


Fig. III.2.b. Double clamp

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 specific gravity $S_v = 1000 \text{ kg/m}^3$.

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

The support distance is limited to a deflection of 5 % of the span length and is related to the temperature of the pipe system.

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.).

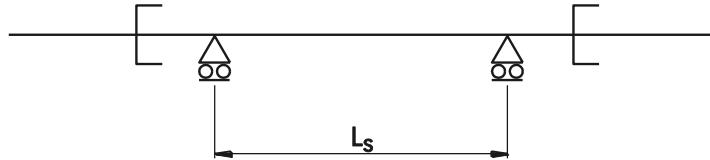


Fig. III.3. Single span length

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

$$L_{S1} = \sqrt{\frac{\sigma * W_B * S_A}{Q_p}} \quad (\text{Eq. III.1.})$$

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 (S_A) depends on the actual stress due to internal pressure:

$$S_A = S_{XT} - S_X \quad (\text{Eq. III.2.})$$

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 (S_X) 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:

$$S_x = \frac{P}{4} * \left(\frac{ID}{T_E} + 1 \right) \quad (\text{Eq. III.3.})$$

For uni-axial loaded systems:

$$S_x = \frac{P}{8} * \left(\frac{ID}{T_E} + 1 \right) \quad (\text{Eq. III.4.})$$

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 Q_P depends on the type of fluid that is transported:

$$Q_P = \frac{(G_B + G_V) * g}{1000} \quad (\text{Eq. III.5.})$$

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

$$L_{S2} = 0.7268 * \sqrt[3]{\frac{E_{XT} * I_Z}{Q_P}} \quad (\text{Eq. III.6.})$$

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 20 °C the temperature correction factor for the E-modulus (R_E) (see table II-h.) shall be applied as follows:

$$E_{XT} = E_X * R_E \quad (\text{Eq. III.7.})$$

Where:

E_{XT}	= Axial bending modulus at elevated temperature	(N/mm ²)
E_X	= Axial bending modulus (see table II-g.)	(N/mm ²)
R_E	= Temperature correction factor (R_{E1} , R_{E2} , R_{E3}) for E-modulus (see table II-h.)	(-)

The single span length (L_S) 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.).

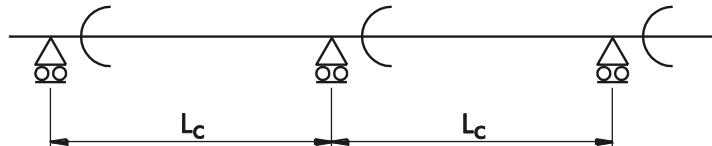


Fig. III.4. Continuous span length

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

$$L_{C1} = \sqrt{\frac{12 * W_B * S_A}{Q_p}} \quad (\text{Eq. III.8.})$$

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:

$$L_{C1} = 1.225 * L_{S1} \quad (\text{Eq. III.9.})$$

B. Continuous span length based on the allowable sag

$$L_{C2} = 1.2429 * \sqrt[3]{\frac{E_{XT} * I_z}{Q_p}} \quad (\text{Eq. III.10.})$$

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:

$$L_{C2} = 1.71 * L_{S2} \quad (\text{Eq. III.11.})$$

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

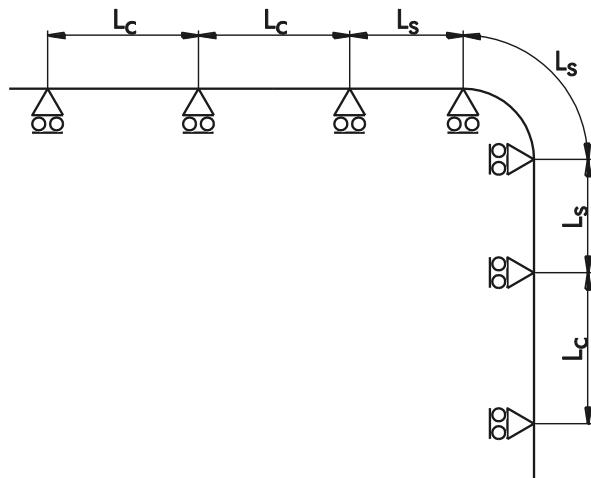


Fig. III.5. Examples of single span length (L_s) and continuous span length (L_c)

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. Specific gravity correction factor (R_s)

Aboveground pipelines which are used for the transportation of fluids with a specific gravity (S_v) other than 1000 kg/m³ 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:

$$L_F = L' * R_s * R_T \quad (\text{Eq. III.12.})$$

Where:

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

Table III-a. Specific gravity correction factor R_s (-)

	Specific gravity of the fluid S_v (kg/m ³)						
	0	600	800	900	1000	1100	1250
R_s	1.55	1.25	1.07	1.03	1.0	0.95	0.90

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

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
1100	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				
	1100	7.0					8.6				
	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				
	1100	8.6					10.5				
	1200	9.0					11.0				
	1400	9.7					11.8				
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				
EST 20	150	3.8					4.6				
	200	4.7					5.7				
	250	5.2					6.4				
	300	5.6					6.9				
	350	6.1					7.4				
	400	6.5					7.9				
	450	6.8					8.4				
	500	7.2					8.8				
	600	8.0					9.8				
	700	8.6					10.5				
	750	8.9					10.9				
	800	9.1					11.2				

Table III-c-2. 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 25	100	3.5	3.4	3.4	3.3	3.2	5.7		5.6	5.4	
	125	3.9	3.8	3.7	3.6	3.5	5.1		5.1	5.1	
	150	4.4	4.3	4.2	4.1	4.0	5.5		5.5	5.5	
	200	5.1	5.1	5.1	5.0	4.8	6.2		6.2	6.2	
	250	5.6	5.6	5.6	5.6	5.6	6.9		6.9	6.9	
	300	6.1	6.1	6.1	6.1	6.1	7.5		7.5	7.5	
	350	6.6	6.6	6.6	6.6	6.6	8.1		8.1	8.1	
	400	7.2	7.2	7.2	7.2	7.2	8.8		8.8	8.8	
	450	7.6	7.6	7.6	7.6	7.6	9.3		9.3	9.3	
	500	8.0	8.0	8.0	8.0	8.0	9.8		9.8	9.8	
EST 32	600	8.7	8.7	8.7	8.7	8.7	10.7		10.7	10.7	
	80	3.2	3.2	3.1	3.0	2.9	5.5	5.4	5.3	5.2	5.0
	100	3.6	3.5	3.5	3.4	3.2	4.7	4.7	4.7	4.7	4.7
	125	4.2	4.1	4.0	3.9	3.7	5.1	5.1	5.1	5.1	5.1
	150	4.5	4.5	4.5	4.4	4.2	5.5	5.5	5.5	5.5	5.5
	200	5.3	5.3	5.3	5.3	5.1	6.4	6.4	6.4	6.4	6.4
	250	5.9	5.9	5.9	5.9	5.9	7.3	7.3	7.3	7.3	7.3
	300	6.6	6.6	6.6	6.6	6.6	8.0	8.0	8.0	8.0	8.0
	350	7.1	7.1	7.1	7.1	7.1	8.7	8.7	8.7	8.7	8.7
	400	7.6	7.6	7.6	7.6	7.6	9.3	9.3	9.3	9.3	9.3
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
EST 50	400	8.8	8.8	8.8	8.8	8.8	10.7	10.7	10.7	10.7	10.7

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	
	1100	9.6				9.6				11.7	
	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	
	1100	11.8	11.8	11.8	11.8	11.8				14.5	
	1200	12.4	12.4	12.4	12.4	12.4				15.1	
	1400	13.3	13.3	13.3	13.3	13.3				16.3	
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	
EST 20	150	4.1	4.0	3.9	3.8	3.7				6.5	
	200	5.0	4.9	4.8	4.6	4.5				7.8	
	250	5.8	5.7	5.5	5.4	5.2				8.7	
	300	6.5	6.4	6.2	6.1	5.9				9.5	
	350	7.3	7.1	6.9	6.7	6.5				10.2	
	400	7.9	7.7	7.6	7.4	7.1				10.9	
	450	8.6	8.4	8.2	8.0	7.7				11.5	
	500	9.2	9.0	8.8	8.5	8.2				12.1	
	600	10.4	10.2	9.9	9.7	9.3				13.4	
	700	11.5	11.2	11.0	10.7	10.3				14.5	
	750	12.1	11.8	11.5	11.2	10.8				14.9	
	800	12.6	12.3	12.0	11.7	11.3				15.4	

Table III-d-2. 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 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
EST 32	600	11.1	10.9	10.6	10.3	10.0	14.7	14.7	14.7	14.7	14.7
	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
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
EST 50	400	9.8	9.6	9.4	9.1	8.8	14.8	14.8	14.8	14.8	14.8

Table III-e-1. Support distance L' (m) for series EST; P = 0.5 * 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	5.7	5.6	5.4	5.3	5.1					
	400	6.2	6.1	5.9	5.8	5.6					
	450	6.7	6.6	6.4	6.2	6.0					
	500	7.2	7.0	6.9	6.7	6.5					
	600	8.2	8.0	7.8	7.6	7.3					
	700	9.0	8.8	8.6	8.4	8.1					
	750	9.5	9.2	9.0	8.8	8.5					
	800	9.9	9.7	9.5	9.2	8.9					
	900	10.5	10.5	10.3	10.0	9.6					
	1000	11.1	11.1	11.0	10.7	10.3					
	1100	11.6	11.6	11.6	11.4	11.0					
	1200	12.1	12.1	12.1	12.1	11.7					
	1400	13.1	13.1	13.1	13.1	12.9					
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	15.0	15.0	15.0	15.0	15.0
	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
	1100	13.4	13.1	12.8	12.4	12.0	17.6	17.6	17.6	17.6	17.6
	1200	14.2	13.8	13.5	13.2	12.7	18.4	18.4	18.4	18.4	18.4
	1400	15.7	15.3	15.0	14.6	14.1	19.8	19.8	19.8	19.8	19.8
EST 16	200	4.6	4.5	4.4	4.3	4.1	7.8	7.7	7.5	7.3	7.0
	250	5.4	5.2	5.1	5.0	4.8	9.2	9.0	8.8	8.5	8.2
	300	6.0	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	6.0	10.9	10.9	10.9	10.6	10.2
	400	7.3	7.2	7.0	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	13.0	13.0	13.0	13.0	13.0
	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	10.0	16.0	16.0	16.0	16.0	16.0
	800	11.6	11.3	11.1	10.8	10.4	16.5	16.5	16.5	16.5	16.5
EST 20	150	4.1	4.0	3.9	3.8	3.7	7.0	6.8	6.7	6.5	6.3
	200	5.0	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	10.0
	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	8.0	7.7	14.0	14.0	14.0	13.6	13.1
	500	9.2	9.0	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	11.0	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	12.0	11.7	11.3	18.7	18.7	18.7	18.7	18.7

Table III-e-2. Support distance L' (m) for series EST; P= 0.5 * 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 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	7.6	7.4	7.2	7.0	6.8
	200	5.4	5.2	5.1	5.0	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	7.0	6.8	6.7	6.5	6.3	12.0	11.7	11.4	11.1	10.7
	350	7.8	7.6	7.4	7.2	7.0	13.3	13.0	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	15.0	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
EST 32	600	11.1	10.9	10.6	10.3	10.0	17.9	17.9	17.9	17.7	17.1
	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
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
EST 50	400	9.8	9.6	9.4	9.1	8.8	16.8	16.4	16.1	15.6	15.1

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.

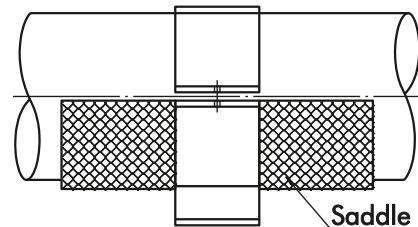


Fig. III.6. Adhesive bonded anchor

B. Laminate build-ups

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

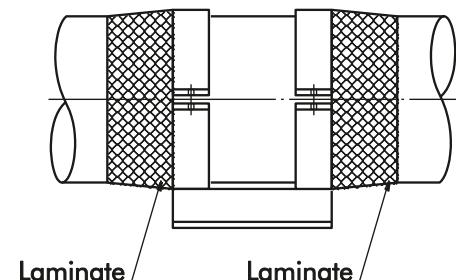


Fig. III.7. Laminated anchor

III.7. Anchor loads

Although Wavistrong pipes have a higher coefficient of linear thermal expansion (γ_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 (P_A) for series EST at a temperature change $\Delta T = 10^\circ\text{C}$, from $10^\circ\text{C} - 20^\circ\text{C}$. The data is obtained from calculations with Eq. III.13., using the E-modulus at the highest temperature which is 20°C .

$$P_A = \frac{\pi}{4} * (OD^2 - ID^2) * E_X * \gamma_L * \Delta T \quad (\text{Eq. III.13.})$$

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/mm ²)
γ_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 (P_A) in table III-f. has to be multiplied by a factor representing the multiple of 10 degrees temperature raise ($\Delta T/10$) 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 than 10°C (P_{AT}) is presented in Eq. III.14.

$$P_{AT} = P_A * \frac{\Delta T}{10} * R_E \quad (\text{Eq. III.14.})$$

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 P_A (N) for series EST at 20 °C and $\Delta T = 10$ °C

ID (mm)	Series EST							
	8	12.5	16	20	25	32	40	50
25								473
40								731
50								1012
65								
80								
100					2179	1756	1440	1582
125						2319	1871	2275
150							2816	3464
200				4426	3234	2880	4199	5186
					5521	3960	5962	7359
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						
1100	67633	87293						
1200	79861	103225						
1400	107357	139085						

Table III-g. End play (mm) and angular deflection ($^{\circ}$) of the RS(L)J

ID (mm)	End play X ↗		Deflection angle α	
	RSLJ	RSJ	RSLJ	RSJ
50	2	53	1.5°	3°
80	3	53	1.5°	3°
100	3	53	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	16	66	1°	2°
1000	16	66	1°	2°
1100	26	76	1°	1°
1200	26	76	1°	1°
1400	26	76	1°	1°

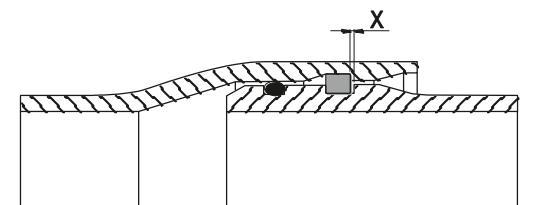


Fig. III.8. End play RSLJ

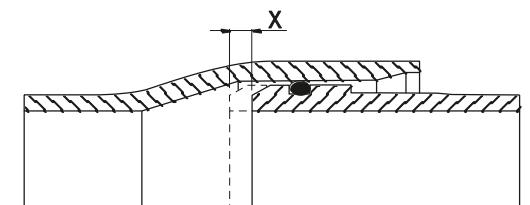


Fig. III.9. End play RSJ

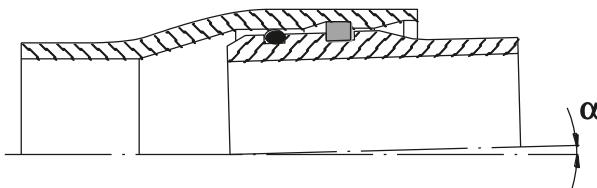


Fig. III.10. Angular deflection RS(L)J

☞ The end play (X) 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 $L_o = 10$ m.

IV. 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 (L_A) must be determined. The fictive anchor length (L_A) can be calculated from the following formula:

$$L_A = 10^{-3} * \frac{ID^2 * P}{4 * OD * F_w} \quad (\text{Eq. IV.1.})$$

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/mm ²)

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

- Soft clay and peaty soils : $0.001 \leq F_w \leq 0.003 \text{ (N/mm}^2\text{)}$
- Sandy clay and sand : $0.003 \leq F_w \leq 0.010 \text{ (N/mm}^2\text{)}$

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 ⁷. 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.

⁷ AWWA Manual M45, Third 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:

$$\frac{\Delta_Y}{D} = \frac{(D_L * W_C + W_L) * K_X}{149 * PS + 61000 * E'} \quad (\text{Eq. IV.2.})$$

Where:

Δ_Y	= Predicted vertical pipe deflection	(mm)
D	= Mean pipe diameter	(mm)
D _L	= Deflection lag factor	(-)
W _C	= Vertical soil load	(N/m ²)
W _L	= 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 * 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:

$$PS \text{ (kPa)} = PS \text{ (psi)} * 6.8948 \quad (\text{Eq. IV.3.})$$

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.
 M_s 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 M_s are close to the E'-values.
On request or for specific installations our engineers can supply calculations using M_s .

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 D_L -value greater than 1.00 is appropriate according the AWWA Manual M45. We advise to use a conservative value of $D_L = 1.25$.

IV.3.1.2. Vertical soil load

The long term vertical soil load (W_c) 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.

$$W_c = \gamma_s * H \quad (\text{Eq. IV.4.})$$

Where:

W_c	= Vertical soil load	(N/m ²)
γ_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. Life 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.

$$W_L = \frac{M_p * P_w * I_f}{L_1 * L_2} \quad (\text{Eq. IV.5.})$$

Where:

W_L	= Life load on pipe	(N/m ²)
M_p	= Multiple presence factor	(-)
P_w	= Wheel load (see table IV-a.)	(N)
I_f	= 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 (P_w)

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

$$I_f = 1 + 0.33 [(2.44 - H) / 2.44] \geq 1.0 \quad (\text{Eq. IV.6.})$$

Where:

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

$$L_1 = t_f + LLDF * H \quad (\text{Eq. IV.7.})$$

Where:

L_1	= Load width parallel to direction of travel	(m)
t_f	= 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: $t_f = 0.25 \text{ m}$

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:

$$H \leq H_{int} \quad (\text{Eq. IV.8.})$$

Then:

$$L_2 = t_w + LLDF * H \quad (\text{Eq. IV.9.})$$

Else:

$$L_2 = (t_w + 1.83 + LLDF * H) / 2 \quad (\text{Eq. IV.10.})$$

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: $t_w = 0.5 \text{ m}$

$$H_{int} = (1.83 - t_w) / LLDF \quad (\text{Eq. IV.11.})$$

IV.3.1.3.1. Calculation notes

- *Life load reduction ratio*

The above calculation assumes that the life load (W_L) extends over the full diameter of the pipe. This may be conservative for large diameter pipe under low fills, where L_1 and $L_2 < OD$.

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 (L_1) should be substituted as shown in Eq. IV.12.

$$L_1 = (\text{axle spacing} + t_f + LLDF * H) / 2 \quad (\text{Eq. IV.12.})$$

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 gravelly 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 D 2487, Practice for classification of soils for engineering purposes; see table IV-d.

↑ Slight = < SPD85/
Moderate = SPD85 < SPD95/
High = > SPD95/
SPD = Standard Proctor Density.

40 % < relative density < 70%
>70 % relative density.

Table IV-d. Soil classification

Group Symbol ^j	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-silt mixtures
GC	Clayey gravels, poorly graded gravel-sand-clay mixtures
SW	Well graded sands, gravelly sands, little or no fines
SP	Poorly graded sands, gravelly 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 fine 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

^j 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:

$$\frac{\sigma_c}{HDB} \leq \frac{1}{F_s} \quad (\text{Eq. IV.13.})$$

Where:

σ_c	= Resulting hoop stress	(N/mm ²)
HDB	= Hydrostatic Design Basis (see table II-f.)	(N/mm ²)
F_s	= Design factor (1.5)	(-)

σ_c is calculated as follows:

$$\sigma_c = \frac{P * D}{2 * T_E} + D_f * E_H * R_c * \left(\frac{\Delta_Y}{D} \right) * \left(\frac{T_T}{D} \right) \quad (\text{Eq. IV.14.})$$

Where:

σ_c	= Resulting hoop stress	(N/mm ²)
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/mm ²)
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	= Nett total wall thickness	(mm)

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

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

If:

$$P > 3 \text{ MPa} \quad (\text{Eq. IV.15.})$$

Then:

$$R_c = 0 \quad (\text{Eq. IV.16.})$$

Else:

$$R_c = 1 - \frac{P}{3} \quad (\text{Eq. IV.17.})$$

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 (S_x) and the circumferential stresses due to internal pressure (S_y) and vertical deflection of the pipe (σ_c), 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)

$$S_x = \frac{1}{2} * S_y \quad (\text{Eq. IV.18.})$$

Where:

$$\begin{aligned} S_x &= \text{Actual axial stress due to internal pressure} && (\text{N/mm}^2) \\ S_y &= \text{Actual hoop stress due to internal pressure} && (\text{N/mm}^2) \end{aligned}$$

$$S_y = \frac{P}{2} * \left(\frac{ID}{T_E} + 1 \right) \quad (\text{Eq. IV.19.})$$

Where:

$$\begin{aligned} S_y &= \text{Actual hoop stress due to internal pressure} && (\text{N/mm}^2) \\ P &= \text{Operating pressure} && (\text{MPa}) \\ ID &= \text{Inner diameter} && (\text{mm}) \\ T_E &= \text{Minimum reinforced wall thickness (see tables II-b. and II-c.)} && (\text{mm}) \end{aligned}$$

B. Non-tensile resistant system (series ESN)

$$S_x = N_{yx} * S_y \quad (\text{Eq. IV.20.})$$

Where:

$$\begin{aligned} S_x &= \text{Actual axial stress due to internal pressure} && (\text{N/mm}^2) \\ N_{yx} &= \text{Poisson ratio hoop/axial (see table II-g.)} && (-) \\ S_y &= \text{Actual hoop stress due to internal pressure (see Eq. IV.19.)} && (\text{N/mm}^2) \end{aligned}$$

Appendix I: List of symbols

Symbol	Explanation	Unit
A	= Structural wall area	(mm ²)
A _B	= Bore area	(mm ²)
CJ	= Conical/Cylindrical adhesive bonded Joint	
c	= Wave velocity	(m/s)
D	= Mean pipe diameter	(mm)
D _f	= Shape factor	(-)
DI	= Structural inner diameter	(mm)
D _L	= Deflection lag factor	(-)
DO	= Structural outer diameter	(mm)
E'	= Modulus of soil reaction	(MPa)
E _H	= Hoop bending modulus	(N/mm ²), (psi)
E _S	= Shear modulus	(N/mm ²)
E _V	= Volumetric E-modulus	(N/mm ²)
E _X	= Axial bending/tensile modulus	(N/mm ²)
E _{XT}	= Axial bending/tensile modulus at elevated temperature	(N/mm ²)
FJ	= Flange Joint	
F _s	= Design factor	(-)
F _w	= Frictional stress between soil and pipe	(N/mm ²)
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/s ²)
H	= Burial depth to top of the pipe	(m)
H _{int}	= Depth at which load from wheels interacts	(m)
HDB	= Hydrostatic Design Basis	(N/mm ²)
HDS	= Hydrostatic Design Stress	(N/mm ²)
ID	= Inner diameter	(mm), (m), (in)
I _f	= Impact factor	(-)
I _R	= Radius of inertia	(mm)
I _Z	= Linear moment of inertia	(mm ⁴)
K _V	= Compression modulus of the fluid	(N/mm ²)
K _X	= Bedding coefficient	(-)
k	= Wall roughness	(mm)

Symbol	Explanation	Unit
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)
L_J	= 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	= Specific gravity correction factor	(-)
R_T	= Temperature change correction factor	(-)

Symbol	Explanation	Unit
S	= Specific Ring Stiffness	(N/m ²)
S _A	= Remaining axial stress	(N/mm ²)
S _b	= Load-dependent safety factor	(-)
S _{eq}	= Equivalent stress	(N/mm ²)
S _{eq(max)}	= Maximum equivalent stress	(N/mm ²)
SF	= Stiffness Factor	(in ² .lb/in)
S _F	= Service factor	(-)
S _f	= Service (design) factor	(-)
S _H	= Allowable hoop stress	(N/mm ²)
S _L	= Specific gravity of the laminate	(kg/m ³)
SPD	= Standard Proctor Density	(%)
S _V	= Specific gravity of the fluid	(kg/m ³)
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)
T _C	= Topcoat thickness	(mm)
T _E	= Minimum reinforced wall thickness	(mm), (m), (in)
T _L	= Liner thickness	(mm)
t _f	= 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	(mm ³)
α	= Ageing and environment reduction factor E-modulus	(-)
ΔH _{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)
Δy/D	= Predicted vertical pipe deflection, fraction of mean diameter	(%)
Δy	= Predicted vertical pipe deflection	(mm)
Δv	= Change in flow velocity	(m/s)
γ _S	= Unit weight of soil	(N/m ³)
γ _L	= Coefficient of linear thermal expansion	(mm/mm.°C)
σ _c	= Resulting hoop stress	(N/mm ²)

Symbol	Explanation	Unit
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	= 0.30480	m
1 yard	= 0.91440	m
1 mile	= 1.60935*10 ³	m
1 sea mile	= 1.852*10 ³	m

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

Area (SI = m²)

1 square inch	= 6.4516*10 ⁻⁴	m ²
1 square foot	= 9.2903*10 ⁻²	m ²
1 square yard	= 0.8361	m ²
1 acre	= 4,046.85	m ²
1 square mile	= 2.58998*10 ⁶	m ²
1 circular inch	= 5.067107*10 ⁻⁴	m ²

Work (SI = Nm = J)

1 foot pound	= 1.35582	J
1 yard pound	= 4.06746	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

Volume (SI = m³)

1 cubic inch	= 16.3871*10 ⁻⁶	m ³
1 cubic foot	= 28.3168*10 ⁻³	m ³
1 cubic yard	= 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

Acceleration (SI = m/s²)

1 foot/second ²	= 0.3048	m/s ²
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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
	= 0.4536	MT/D kg/h

Force (SI = N)

1 pounds force	= 4.4482	N
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Heat

1 Btu/pound	= 2.326	kJ/kg
1 Btu/hour	= 0.2931	W
1 Btu/hour.foot ² .°F	= 5.678	W/m ² .°C
1 Btu/pond.°F	= 4.187	kJ/kg.°C
1 Btu/hour.foot ²	= 3.155	W/m ²
1 Btu.foot/hour.foot ² .°F	= 1.731	W/m.°C
1 foot ² .hour.°F / Btu	= 0.1761	m ² .°C/W

Moment of inertia (SI = m⁴)

1 inch ⁴	= 4.162*10 ⁻⁶	m ⁴
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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

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/m²)

1 pound/inch ²	= 0.0703*10 ⁴	kg/m ²
1 pound/foot ²	= 4.8825	kg/m ²
1 pound/yard ²	= 0.5425	kg/m ²

Density (SI = kg/m³)

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/m² = 10⁻⁵ bar)

1 pound/inch ²	= 6.89476*10 ³	N/m ²
1 pound/foot ²	= 47.876	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

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

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

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

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

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

Heat

1 kilo Joule/kilo	= 0.42992	Btu/lb
1 Watt	= 0.341180	Btu/h
1 Watt/metre ² .°C	= 0.17612	Btu/h.ft ² .°F
1 Watt/metre ²	= 0.316957	Btu/h.ft ²
1 Watt/metre.°C	= 0.5777	Btu.ft/h.ft ² .°F
1 metre ² .°C/Watt	= 5.67859	ft ² .hr.°F/Btu
1 kilo Joule/kilo.°C	= 0.23883	Btu/lb.°F

Mass

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

Velocity

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

Mass per length

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

Acceleration

1 metre/second ²	= 3.28084	ft/s ²
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Mass per area (specific pressure)

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

Flow rate

1 metre ³ /hour	= 37.32736	ft ³ /h
	= 4.40335	gallons/min

Density

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

Mass base

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

Moment of inertia

millimetres ⁴	= 2.40269×10^{-6}	inch ⁴
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Force

1 Newton	= 0.22481	lbf
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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/metre ²	= 9.324	lg tons/ft ² (Eng)
	= 0.6475	lg tons/in ² (Eng)
	= 0.725	srt tons/in ² (US)

Conversion figures for metric units into SI-units
Length (SI = m)

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

Area (SI = m²)

1 km ²	= 10 ⁶	m ²
1 cm ²	= 10 ⁻⁴	m ²
1 mm ²	= 10 ⁻⁶	m ²

Volume (SI = m³)

1 dm ³	= 1 litre	= 10 ⁻³	m ³
1 cm ³		= 10 ⁻⁶	m ³
1 mm ³		= 10 ⁻⁹	m ³

Mass (SI = kg)

1 milligram	= 10 ⁻⁶	kg
1 gram	= 10 ⁻³	kg
1 metric ton	= 10 ³	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/mm ²	= 10 ⁻³	kg/mm ²
	= 10 ³	kg/m ²

Density

1 gram/dm ³	= 1	gram/ltr
	= 10 ⁻³	kg/dm ³
	= 1	kg/m ³

Pressure

1 bar = 10 ⁵ Pa	= 10 ⁵	N/m ²
1 kgf/cm ²	= 9.8066	Pa
1 atm	= 101.325*10 ³	Pa
1 at	= 98066.5	Pa
1 Torr	= 133.322	Pa
1 metre head of water	= 9.80665*10 ³	Pa
1 metre head of mercury	= 133.322*10 ²	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*10 ⁶	J
1 kcal	= 4186.8	J
1 metric horse power hour	= 2.64780*10 ⁶	J
1 erg	= 1 dyn.cm	= 10 ⁻⁷ J

Acceleration

g = gravitation	= 9.8067	m/s ²
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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	m ³ /h
1 m ³ /h	= 0.2778*10 ⁻³	m ³ /s

Mass base

1 kg/h	= 24.0	MT/D
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Force

1 kgf	= 9.80665	N
1 dyn	= 1 g.cm/s ²	N

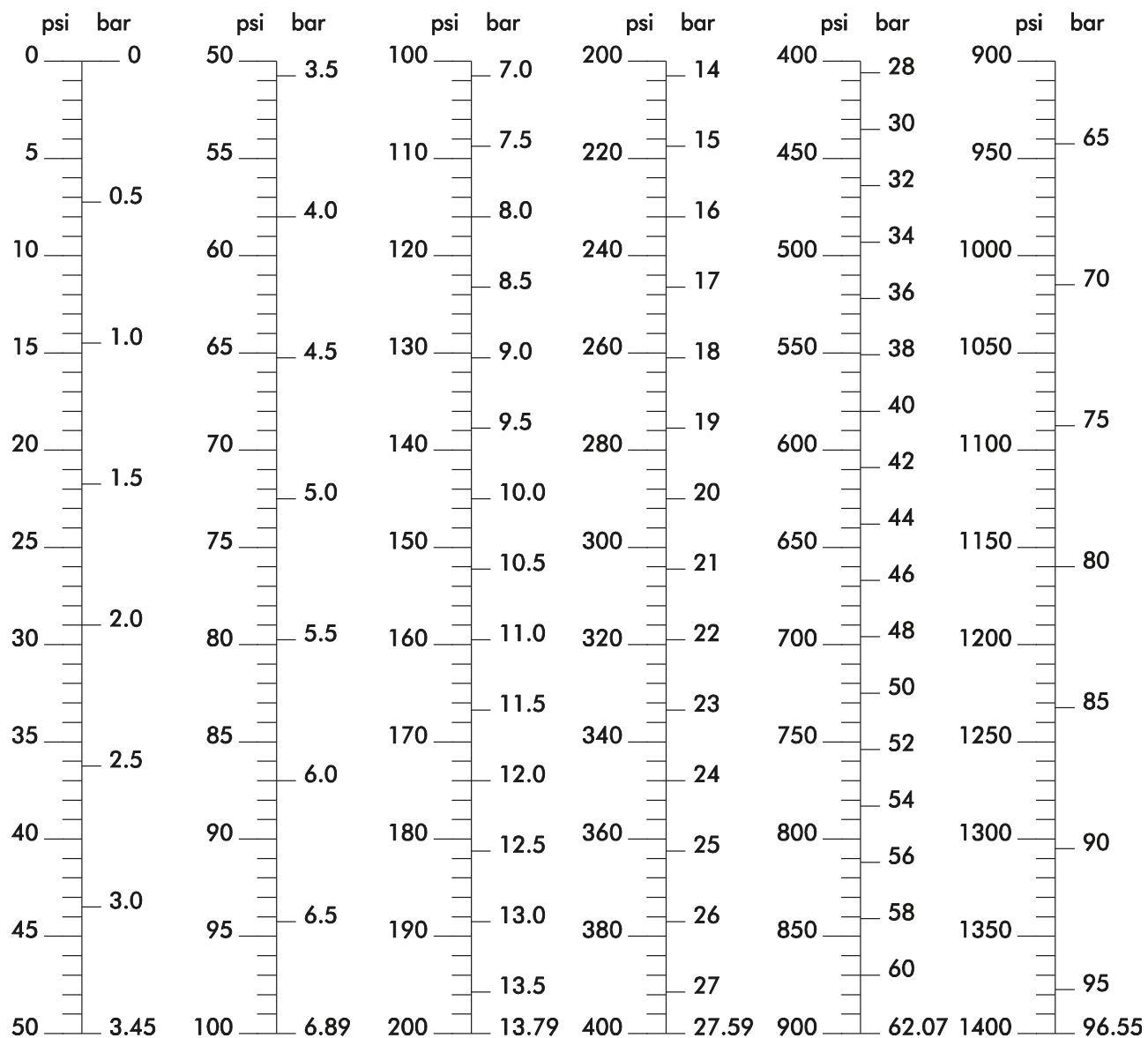
Heat

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

