GERMAN ATV RULES AND STANDARDS

WASTEWATER - WASTE

ADVISORY LEAFLET
ATV - M 127E, Part 2

Part 2: Static Calculation for the Rehabilitation of Drains and Sewer Using Lining and Assembly Procedures

Supplement to Standard ATV-A 127E

January 2000

ABWASSER • ABFALL • GEWÄSSERSCHUTZ
GERMAN ASSOCIATION FOR THE WATER ENVIRONMENT

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Notes for Users

This ATV Advisory Leaflet is the result of honorary, technical-scientific/economic collaboration which has been achieved in accordance with the principles applicable therefor (statutes, rules of procedure of the ATV and ATV Standard ATV-A 400). For this, according to precedents, there exists an actual presumption that it is textually and technically correct and also generally recognised.

The application of this Advisory Leaflet is open to everyone. However, an obligation for application can arise from legal or administrative regulations, a contract or other legal reason.

This Advisory Leaflet is an important, however, not the sole source of information for correct solutions. With its application no one avoids responsibility for his own action or for the correct application in specific cases; this applies in particular for the correct handling of the margins described in the Advisory Leaflet.

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Contents

1 Preamble

In accordance with DIN EN 752-5 rehabilitation procedures are subdivided as follows:

- repair procedures
- renovation procedures
- renewal procedures.

The methods of lining and assembly coming under rehabilitation procedures are covered in this Advisory Leaflet with its associated appendices.
The new pipe installed through lining inside the old pipe is referred to below as the liner. Currently the following renovation procedures are recognised for this:

- hose lining
- pipe lining (short pipe, long pipe, pipe string lining and reformed lining)
- wrapped tube lining
- napped width lining
- assembly methods.

As already stated in the foreword to ATV-DVWK Standard A-127E, a dimensioning of the liners using ATV-A 127E is not planned and not permitted. In particular this standard does not contain the following characteristics which are of significance for the static calculation:

- imperfections with the bedding of the liner in the old pipe
- long-term stress detection for the long-term effects of external water pressure
- contact pressure problems
- necessary non-linear calculation (second-order theory due as a rule to concurrent occurrence of thinner wall thicknesses, small elasticity modules and high longitudinal forces in the liner wall.

These particular features are taken into account in this Advisory Leaflet ATV-M 127, Part 2.

The dimensioning rules apply for the constructional and service conditions. Only stable old pipe/soil systems (= Load Condition 1 in accordance with ATV-M 143, Part 3) are dealt with.

For standard cases the calculations are supported by coefficient tables, so that - as usual in ATV-A 127 - manual calculations continue to be possible. For special cases, such as oval profiles, ranges of values not investigated, for example of the modulus of elasticity and the wall thickness, part liners and other construction methods not covered in this advisory leaflet, separate investigations are necessary which can be modelled on rules formulated in the advisory leaflet.

With the aid of the advisory leaflet initial dimensioning assistance is provided through which both planning safety is achieved and economic solutions are made possible.

The details necessary for the calculations are to be made available by the customer. See also Sect. 3.1.
The ATV Working Group “Pipe Statics” requests the users of this advisory leaflet for information on experience with application as the technique of pipeline rehabilitation are not yet complete and new areas of application, procedures and materials can also influence methods of calculation.

2 Symbols

Symbol	Unit	Designation
Drawing-in (pipe string lining)		
a_1,a_2	m	Lever arm of restraints on the old pipe and possibly on the edge of the open cut
$A_1,\bar{A}_1$	kN	Bearing forces at the end of the old pipe
$A_2,\bar{A}_2$	kN	Bearing forces at the edge of the open cut
A_Q	m^2	Area of the liner cross-section (annulus)
$A_{Q,n}$	m^2	Net area of the liner cross-section
$d_{L,e},d_{L,i}$	mm	External/internal diameter of the liner
$E_{\sigma = 3}$	N/mm²	Elasticity modulus of a PE-HD liner with σ = 3 N/mm^2
$E_{\sigma = 15}$	N/mm²	Elasticity modulus of a PE-HD liner with σ = 15 N/mm^2
E_m	N/mm²	Effective elasticity modulus of the liner
$\overline{g}_L, \overline{g}'_L$	kN/m	Dead-weight of the liner (referred to 1 m pipe length)
h_{OC}	m	Depth of the open cut
I_Q	m^4	2nd moment of area of liner cross-section (annulus)
k_υ	-	Factor to take into account the temperature on drawing in
l_{OC}	m	Required length of the open cut
l_3	m	Distance of the additional trestle from open cut wall
$M_{1,g},M_{2,g}$	kNm	Bending moment on old pipe and trench edge as result of dead-weight g
$M_{1,h},M_{2,h}$	kNm	Bending moment on old pipe and trench edge due to lifting by h
W_Q	m^3	Section modulus of liner cross-section
Z_g	kN	Drawing-in force as result of friction of pipe string (old pipe, ground)
Z_M	kN	Drawing-in force as result of deflection on the old pipe and trench edge
$Z_ß$	kN	Drawing-in force as result of bending in old pipe
$R_{b,perm}$	m	Permitted radius of bend on drawing-in
ε_{perm}	%	Permitted elongation associated with σ_{perm}
$\varepsilon_{b,perm}$	%	Permitted elongation associated with $R_{K,perm}$
σ_{perm}	N/mm^2	Permitted stress
$\sigma_{b,perm}$	N/mm^2	Permitted stress associated with $R_{K,perm}$
α_w	-	Welding factor
Δh	mm	Play of liner in the old pipe
Δh_3	mm	Additional lift dimension in the vicinity of the edge of trench
φ_G,φ_P	-	Ground slope, slope of old pipe
$\varepsilon_T,\varepsilon_C$	%	Elongation in the liner wall (x-direction)
μ_G	-	Friction coefficient of pipe string in the old pipe, on the ground
μ_R	-	Coefficient for frictional resistance on deflecting rollers
σ_T,σ_C	N/mm^2	Tensional/compression stresses in the liner wall (x-direction)
υ	°C	Temperature on drawing in
Filling:		
E_F	N/mm²	Elasticity module of the filler
F_F	kN/m	Resultant loading from filler weight
F_g	kN/m	Resultant loading from dead-weight of pipe
F_w	kN/m	Resultant loading from water filling
g_L	kN/m²	Dead-weight of liner wall
h_F	m	Height of liquid filler above bottom of liner
m_g,m_F,m_O,m_W	-	Bending moment coeff. for dead-weight, filler, overpressure, water filling
M_g,M_F,M_O,M_W	kNm/m	Bending moment from dead-weight, filler, overpressure, water filling
n_g,n_F,n_O,n_W	-	Normal force coeff. for dead-weight, filler, overpressure, water filling
N_g,N_F,N_O,N_W	kN/m	Normal force from dead-weight, filler, overpressure, water filling
α_S	°	Angle between spacers with filling

α_B	°	Bedding angle of liner in old pipe with filling
Δd_v	mm	Change of diameter
δ_v	%	Relative vertical change of diameter
γ_F	kN/m³	Unit weight of filler
γ_L	kN/m³	Unit weight of liner
γ_W	kN/m³	Unit weight of water filling
Service condition:		
A	mm²/mm	Cross-sectional area of the liner wall
DN	mm	Nominal width of old pipe
d_i/d_e	mm	Internal/external diameter of old pipe
e_J	mm	Eccentricity of the assumed old pipe joints
E_L	N/mm²	Elasticity modulus of liner
$(EI)_L$	N/mm²	Flexural strength of the liner
g_L	kN/m²	Dead-weight of liner wall
$g_{L,crit}$	kN/m²	Critical dead-weight of liner wall
h	m	Covering height above pipe crown
$h_{W,Inv,crit}$	m	Height of water level above invert of liner
h_W'	m	Height of water level above crown of old pipe
k*	-	Parameter with buckling detection for *profiled* pipes (use for r_L/s_L)
K_2	-	Earth pressure ratio in soil zone 2 (pipeline zone)
K_2'	-	Calculated earth pressure ratio in soil zone 2 (Old Pipe Condition III)
m_{pe},m_q	-	Bending moment coefficients for external water pressure, vertical total load
M_{pe},M_q	kNm/m	Bending moment from external water pressure, vertical total load
n_{pe},n_q	-	Normal force coefficients for external water pressure, total vertical load
N_{pe},N_q	kN/m	Normal force from external water pressure, vertical total load
p_e	kN/m²	External water pressure
$p_{e,crit}$	kN/m²	Critical external water pressure
p_i	kN/m²	Internal pressure
p_E	kN/m²	Soil stresses as result of earth load and surface load (Old Pipe Condition III)
p_V	kN/m²	Soil stresses as result of traffic load (Old Pipe Condition III)
$p_{V,crit}$	kN/m²	Critical traffic load
p_υ	kN/m²	Contact pressure between liner and old pipe as a result of warming
$p_{\upsilon,crit}$	kN/m²	Critical contact pressure with warming of the liner
q_h	kN/m²	Horizontal soil stress at the pipe (Old Pipe Condition III)
q_h^*	kN/m²	Horizontal bedding reaction pressure (Old Pipe Condition III)
q_v	kN/m²	Vertical soil stress at the pipe (Old Pipe Condition III)
$q_{v,crit}$	kN/m²	Critical vertical total load
$r_{L,e}$	mm	External radius of the liner
r_L	mm	Average radius of the liner
r_m	mm	Average radius of the old pipe
s	mm	Wall thickness of the old pipe
s_L	mm	Wall thickness of the liner
S_{Bh}	N/mm²	Horizontal bedding stiffness of the soil
S_L	N/mm²	Pipe stiffness of the liner
w_v	mm	Depth of the local prestrain
$w_{AR,v}$	mm	Articulated ring deformation of the old pipe (Old Pipe Conditions II and III)
w_s	mm	Gap width between liner and old pipe (annular gap)
Δw_s	mm	Annular gap between liner and old pipe caused by articulated ring expansion (Old Pipe Condition III only)
W,W_i,W_e	mm³/mm	Section modulus of the liner wall
α_{ST}	-	Snap-through coefficient for external water pressure
$\alpha_{ki},\alpha_{,ke}$	-	Correction factor for curvature of the liner wall (internal, external)
α_{qv}	-	Snap-through factor for earth and traffic loads
α_t	1/K	Coefficient of temperature expansion

γ_{nec}	-	Necessary safety
γ_{bT}, γ_{bC}	-	Safety with verification of stress
γ_I	-	Safety against instability
γ_S	kN/m^3	Unit weight of the soil
γ_S'	kN/m^3	Unit weight of the soil under water
γ_L	kN/m^3	Unit weight of liner
γ_W	kN/m^3	Unit weight of groundwater
δ_v	%	Relative vertical change in diameter
$\delta_{v,el}$	%	Elastic relative vertical change in diameter
ε_P	-	Extreme fibre limiting strain, arithmetic value
$\Delta\upsilon$	K	Temperature change
φ_v	°	Position of the local prestrain
$2\varphi_l$	°	Width of local prestrain
κ_v	-	Reduction factor for local prestrain w_v
$\kappa_{AR,v}$	-	Reduction factor for articulated ring prestrain $w_{GR,v}$ (ovalisation)
κ_s	-	Reduction factor for gap width w_s
$\kappa_{v,s}$	-	Common reduction factor for prestrain w_v (local) and $w_{GR,v}$ (ovalisation) as well as gap width w_s
σ_{bT}	N/mm^2	Bending tensile strength of the liner, arithmetic value
σ_{bC}	N/mm^2	Bending compressive strength of the liner, arithmetic value
σ_e	N/mm^2	Stress on the outside of the liner
σ_i	N/mm^2	Stress on the inside of the liner
σ_P	N/mm^2	Bending tensile strength, arithmetic value

3 Technical Details

3.1 Condition of the Old Pipeline, General

The following information on the old pipeline is required:

- pipe material and wall thicknesses (e.g. cores)
- soil conditions (e.g. type of soil, covering, max/min groundwater, penetrometry)
- damage picture (comp. ATV Advisory Leaflet ATV-M 143E, Part 1, Section 5.

The following information on the old pipeline should be available:

- static calculation
- pipe support
- pipe connections and sealing.

With brickwork sewers the following additional information is required:

- wall thickness (if required variable over the circumference)
- stability of mortar and bricks (also distributed over the wall thickness)
- formation of the invert (moulded brick or similar)
- condition of joints.

3.2 Condition of the Old Pipeline from the Static Aspect

3.2.1 Non-rehabilitated Old Pipeline

Old Pipe Condition I:

Old pipe alone capable of bearing (e.g. leaks in pipe connections, walls have no cracks except hairline cracks)[1)].

Old Pipe Condition II:
Old pipe-soil system alone capable of bearing (e.g. longitudinal cracks with small pipe deformation with checked functional lateral bedding. Confirmed e.g. through long-term observation and/or penetrometry)[1).].

Old Pipe Condition III:
Pipe-soil system in the long-term no longer alone capable of bearing; significant deformation; compared with Old Pipe Condition II the liner is also stressed by earth and traffic loads[1)].
Further explanation on the old pipe conditions see Annex A3/2.
Special cases for which, if necessary, separate static considerations are to be made:

- wide annular cracks or wide gaps in sleeves with a width > $d_i/10$ or > $10 \cdot s_L$, a calculation according to the theory of thin shells is to be carried out.
- missing pipe sections, with missing parts of pipe with an edge length > $d_i/2$, a calculation according to the theory of thin shells is to be carried out.
- sleeve displacement laterally and longitudinally[2)].
- formation of fragments and holes in the pipe wall.
- damaged inlets and shaft connections.
-

[1)] The Old Pipe Conditions I to III described here are assigned to Load Case 1 "The sewer to be rehabilitated is stable" in ATV-M 143, Part 3, whereby the actual stability γ > 1,0 (no collapse).
[2)] According to the current state of knowledge sleeve displacements have no load bearing reduction influence so far as they are not caused by pipe fracture.

3.2.2 Non-rehabilitated Old Pipeline

Pipe-soil system no longer alone capable of bearing; presumption of a formation of cracks for a point in time after rehabilitation (e.g. later constructional measures in the vicinity of the sewer).

If Old Pipe Condition I is present with the rehabilitation, one must, however, reckon with crack formation *after* rehabilitation, thus a concentration factor λ_P > 1 is possible (comp. Sect. 6.3.2.4).

The transfer of the compression forces in the old pipe must be guaranteed. If required, compressive strengths from core borings are to be enlisted.

3.3 Condition of the Shafts from the Static Aspect

For shafts, statements made under Sect. 3.2.1 for Old Pipe Condition I and, if required, Condition II apply analogously.

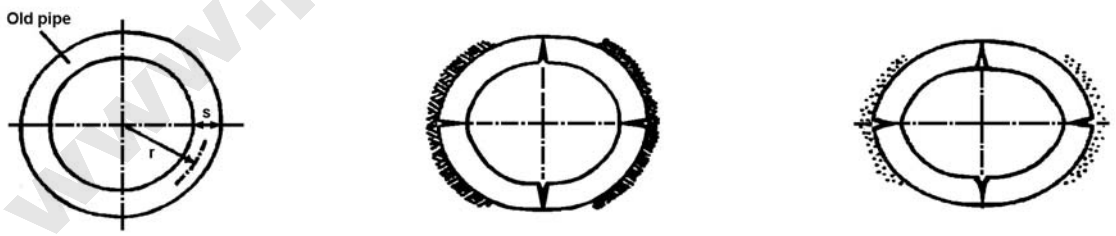

Fig. 1: Old pipe conditions
a) Old Pipe Condition I b) Old Pipe Condition II c) Old Pipe Condition III

Table 1: Load cases arising

	Old pipe condition		
	I	II	III
Time of formation of longitudinal cracks	-	Before rehabilitation	Before rehabilitation
Load case:			
External water pressure p_e	X	X	X
Internal pressure p_i	X	X	X
Earth loads p_E	-	-	X
Concentrations factor λ_P	-	-	< 1 *)
Traffic loads p_V	-	-	X

*) Comp. Sect. 6.3.2.4

Table 2: Material characteristic values of liners

	Arithmetic value of the elasticity modulus[3]		Unit weight	Bending tensile/compressive strength, arithmetic value[4]	
	E_L Short-term	Long-term	γ_L	σ_{bT}/σ_{bC} Short-term	Long-term
	N/mm^2	N/mm^2	kN/m^3	N/mm^2	N/mm^2
Polyvinyl chloride (PVC-U)	3,000 [5, 6]	1,500 [5, 6, 7]	14 [8]	90 [6, 9, 10]	50 [6, 9, 10]
Polypropylene (PP) [11]					
PP-B and PP-H [12]	1,250 [5, 6]	312 [6, 14]	9 [15]	39 [6, 9, 10]	17 [6, 9, 10]
PP-R [13]	800 [5, 6]	200 [6, 14]	9 [15]	27 [6, 9, 10]	14 [6, 9, 10]
Polyethylene, high density (PE-HD) [16]	800 [5, 6]	160 [6, 17]	9.4 [18]	21 [6, 9, 10]	14 [6, 9, 10]
Unsaturated polyester resin, glass-fibre reinforced (UP-GF)	[6, 19]	[6, 20]	17.5	[6, 21]	[6, 21]
Unsaturated polyester resin, synthetic-fibre reinforced (UP-SF)	[22]	[22]	13.5	[22]	[22]
Fibre cement	20,000		20	[23]	
Steel (stainless) [24]	170,000		78.5	[25]	

3) The figures given are arithmetic values which are determined from measurement of deformation.
4) The compression stress can also be relevant in particular with thin-walled liners.
5) Tested i.a.w. DIN 54852 (4 point creep bending test), test description i.a.w. DIN 53457, test piece manufacture i.a.w. DIN 16776-2.
6) Higher arithmetic values can be enlisted if these are verified for the material employed.
7) Determined from the short-term value and the creep ratio (2.0) i.a.w. DIN EN 1401-1 and DIN EN ISO 9967 with characteristic values for 2 years for the description of the long-term ratio.
8) I.a.w. DIN EN 1401-1.
9) For plastics the bending tensile strength is designated and given as flexural strength.
10) Smallest value (under 95 % fractile) i.a.w. the Round Robin Test of the raw material producer as well as on the basis of Test Report No. 36893/98-II of the SKZ Süd-deutsches Kunstoffzentrum [South German Synthetic Material Centre] Würzburg.
11) PP-B = Block-Copolymer; PP-H = Homopolymer; PP-R = Random Copolymer.
12) DIN EN 1852-1.
13) DIN EN 1852 and DVS 2205-2, Supplement 1 (Issue 08/97).
14) Determined from the short-term value and the creep ratio (4.0) i.a.w. DIN EN 1852-1 and DIN EN ISO 9967 with characteristic values for 2 years for the description of the long-term ratio.
15) I.a.w. DIN EN 1852-1.
16) PE-HD as PE 63, PE 80 or PE 100 i.a.w. with DN EN ISO 12162.
17) Determined from the short-term value and the creep ratio (5.0) i.a.w. prEN 12666-1 and DIN EN ISO 9967 with characteristic values for 2 years for the description of the long-term ratio.
18) I.a.w. prEN 12666-1.
19) $S_{O,min}$ i.a.w. prEN 1636.
20) Determined from the short-term value and the creep ratio (2.0) characteristic values for 2 years for the description of the long-term ratio. Tests take place i.a.w. DIN EN 1228 (short-term) and DIN EN 1225 (long-term).
21) $\varepsilon_P = \pm 4.28 \cdot s / d_m \cdot \Delta d_{frac} / d_m$ i.a.w. prEN 1636 (short- and long-term) with the respectively relevant values for s and d_m.
22) Test report of a recognised or accredited test agency necessary. 95 % fractile values are to be used.
23) DIN EN 588; the ring bending tensile strengths are calculated from the minimum values of the crushing loads (95 % fractile, AQL 4 %).
24) DIN17440, DIN 17441, DIN 17455, DIN 17456, DIN EN ISO 3506-1 to 3.

25) Assignment to St 37/St 52 takes place with the aid of $R_{p0.2}$ as apparent limit of elasticity.

3.4 Pipe Material Characteristic Values

3.4.1 Liner Materials

The material characteristic values in accordance with Table 2 are, if required, to be reduced for influences conditioned by technical construction methods. The size of the reduction is, in the individual case, to be verified by recognised or accredited testing agencies. Such reductions of material characteristics occur with, for example:

- long elongations during installation
- seams in woven textile hoses
- liners with nap
- notch effects (stress concentrations).

3.4.2 Materials for the Filling of the Annular space

With the employment of filler, for example in accordance with ATV-M 143 Part 3 (4.93), 6.1.1. to fill the annular space and the long-term support of the liner the following characteristic values must be known:

- amount of swelling/amount of shrinkage
- modulus of elasticity
- unit weight
- strengths (compressive strength and, if necessary, bending tensile strength)
- with the employment of adhesion; shear strength.

The material characteristic values are, if necessary, to be reduced for influences conditioned by technical construction procedures. The scale of the reduction is to be verified in individual cases (e.g. segregation, uneven hardening, inclusion of air).

4 Construction Work

4.1 Preparatory Work

A static calculation of the constructional and operational conditions in accordance with Sects. 5 and 6, in which the local conditions are taken into account, is to be carried out before the execution of work.

The pipeline is to be dried and cleaned. Deposits and obstacles (e.g. projecting connections) are to be removed, see also ATV-M 143, Part 3 (4.93) 5.4.1. Larger disruptions to the geometry of the pipe (washing out of the pipe invert, changes, annular gaps, holes, fragments, offsets) are to be smoothed out using suitable materials.

Measures to seal against infiltration water are to be taken. In this way the incidence of pockets of water collecting is to be prevented before the final hardening of the liner.

The pipe diameter and deformations of the old pipeline are to be determined with appropriate accuracy. The accuracy of the bore measurement is to be matched to the rehabilitation method employed and assumptions in the static calculation, for example, with the rehabilitation of sewers with pipe offsetting, if liners with small capability for elongation are employed.

4.2 Installation Methods

Differentiation is made between draw-in, push-in and roll-in methods.

For installation, measures are to be provided for the reduction of friction (sufficient annular space, lubricants) and for the prevention of damage to the liner surface. attention is to be paid for the observation of radii of bends, comp. permitted $R_{b,perm}$ in Sect. 5.1.1.

4.2.1 Methods with Annular Space Filling

Currently the following methods are used:

- pipe lining (short pipe, long pipe, pipe string)
- wrapped pipe lining
- napped band lining.

With the necessary annular ring filling, attention is to be paid, inter alia, to the following:

- implementation with/without spacers
- checking of the filling achieved (e.g. through comparison of volume)
- if necessary, planning of filling by sections
- avoidance of segregation
- limitation of pressing pressure dependent on the pipe stiffness of the liner (comp. Sect. 5.2).

4.2.2 Methods without Annular Space Filling (Close-Fit Method)

Currently the following methods are employed:

- hose methods
- prestrained liner with later reforming.

Gaps between old pipe and liner are to be kept small (arithmetical minimum values see. 6.3.1.1).

4.2.3 Installation Procedures

Currently the following methods are employed:

- full linings with installation joints
- partial linings (invert, gas space)
- shaft linings.

With doweled partial and shaft linings the remaining gap is to be estimated on the safe side taking into account the resilience of the fixing.

5 Verification for Structural Conditions

5.1 Drawing-in of the Pipe String

5.1.1 Material Characteristic Values, Buckling Limiting Values

Note: the verification equations for the pipe string lining are given below for PE-HD pipes. With other materials the procedure is analogous.

With the drawing-in of a pipe string made from PE-HD without the danger of buckling of the pipe wall, according to Table 2 the limiting stress σ_P = 21 N/mm^2 and with the employment of safety for the installation conditions the permitted $\sigma_{perm} \cong 15$ N/mm². To this stress belongs the short-term modulus $E_{\sigma=15}$ = 500N/mm2 and the elongation ε_{perm} = 3 % according to the DVS Standard 2205.

With a danger of buckling of the pipe wall the bending radius of the pipe string on drawing-in is to be limited to (valid with 1.5 times buckling safety)

$$R_{b,perm} = 1.34 \cdot \frac{(d_{L,e} - s_L)^2}{s_L} \tag{5.1}$$

To this belongs the permitted elongation

$$\varepsilon_{b,perm} = \frac{d_{L,e}}{2 \cdot R_{b,perm}} \cdot 100\% \le 3\% \tag{5.2}$$

Due to the danger of buckling the stress $\sigma_{b,perm}$ is to be reduced appropriately, comp. Table 3. The associated E modulus can be approximately interpolated:

$$E_\sigma = E_{\sigma=3} + \frac{E_{\sigma=3} - E_{\sigma=15}}{3 - 15} \cdot (\sigma - 3) \tag{5.3}$$

with $E_{\sigma=3}$ = E modulus with σ = 3 N/mm²

Table 3: Permitted bends, permitted elongations, permitted stresses, stress dependent E moduli and temperature coefficients for PE-HD liners (valid for υ = 20 °C and PE-HD with $E_{\sigma=3}$ = 970 N/mm²)

PN	SDR $=d_{L,e}/s_L$	$R_{b,perm}/ d_{L,e}$	$\varepsilon_{b,perm}/\varepsilon_{perm}$	$\varepsilon_{b,perm}/\varepsilon_{perm}$	$E_{\sigma b,perm}$	k_υ
bar	-	-	%	N/mm²	N/mm²	-
3.2	32.25	40.5	1.23	9.1	737	0.022
4	26.00	32.2	1.55	10.5	679	0.027
6	17.67	21.1	2.37	13.4	564	0.033
10	11.00	12.2	3.00	15.0	500	0.037

In addition the variability of the stresses and thus of the E modulus along the length of the open cut and the pipe diameter is taken into account as follows:

$$E_m = \frac{E_{\sigma=3}}{3} \cdot \frac{a^3}{a^2/2 - a + \ln(1+a)} \tag{5.4}$$

with $a = \frac{E_\sigma - E_{\sigma=3}}{E_{\sigma=3}}$

If drawing in takes place at temperatures deviating by 20 °C then the open cut lengths established according to the following sections can be corrected as follows:

$$l_{OC\upsilon} = l_{OC} \cdot (l - k_\upsilon \cdot \Delta\upsilon) \tag{5.5}$$

with $\Delta\upsilon > 0$ with warming and k_υ in accordance with Table 3.

5.1.2 Case 1: Restraint

5.1.2.1 Sectional Measurements

With the drawing-in of a pipe string according to Fig. 2 with restraint, there result bending moments and tensile forces in the liner at the old pipe (clearance ≅ 0) and at the edge of the trench (e.g. using a reduction machine).

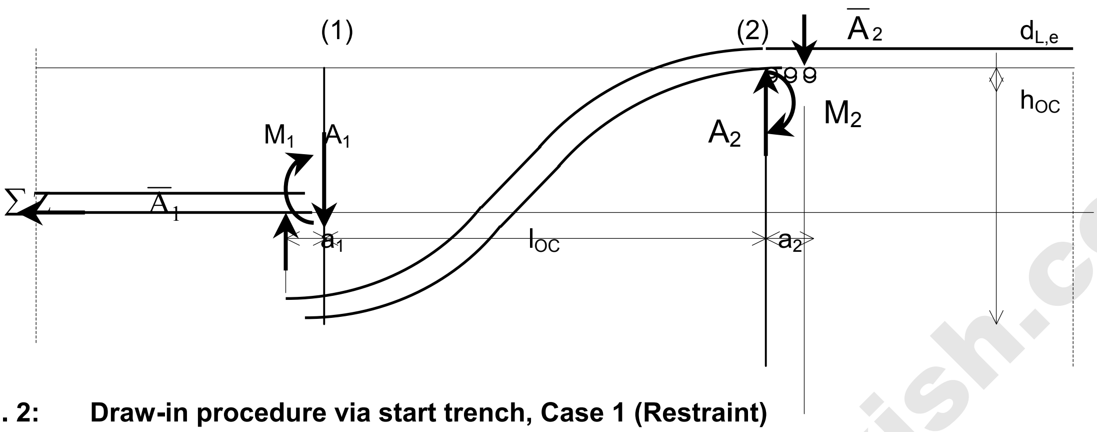

Fig. 2: Draw-in procedure via start trench, Case 1 (Restraint)

The *bending moments* result from the draw-in geometry as

$$M_{1,h} = 6 \cdot E_m \cdot \frac{I_Q \cdot h_{OC}}{l_{OC}^2}, \quad M_{2,h} = -M_{1,h} \tag{5.6a}$$

with the 2nd moment of area of the pipe cross-section

$$I_Q = \frac{\pi}{64} \cdot (d^4_{L,e} - d^4_{L,i}) \tag{5.6b}$$

and from the dead-weight $\bar{g}_L$ of the liner in the longitudinal direction as

$$M_{1,g} = M_{2,g} = -\frac{\bar{g}'_L \cdot l_{OC}^2}{12} \tag{5.7a}$$

with $$\bar{g}'_L = \bar{g}_L \cdot \frac{\sqrt{l_{OC}^2 \cdot h_{OC}^2}}{l_{OC}} \tag{5.7b}$$

$$\bar{g}'_L = A_Q \cdot \gamma_L \tag{5.7c}$$

and $$A_Q = \frac{\pi}{4} \cdot (d^2_{L,e} - d^2_{L,i}) \tag{5.7d}$$

The bearing forces of the liner in the area of the guides are required for the determination of the *tensile forces* and the dimensioning of the mounting structures. With the free clamping length a_1 of the liner in the old pipe the bearing force $\bar{A}_1$:

$$\bar{A}_1 = \frac{M_{1,h}}{a_1} \tag{5.8}$$

The free clamping length can be estimated with $a1 \cong 2 \cdot d_{L,e}$.

For the bearing force A_1 the following applies:

$$A_1 = \bar{A}_1 - \bar{g}'_L \cdot \frac{l_{OC}}{2} + 12 \cdot E_m \cdot I_Q \cdot \frac{h_{OC}}{L_{OC}^3} \quad (5.9)$$

With a clearance of $\Delta h > 0$ of the liner in the old pipe the diagrams in Appendix A1 can also be used approximately for A_1. With the inner lever arm a_2 of the reducing machine, the bearing force $\bar{A}_2$ is

$$\bar{A}_2 = \frac{|M_{2,h}|}{a_2} \quad (5.10)$$

Thus the bearing force at the edge of the trench is

$$A_2 = \bar{A}_2 + \bar{g}'_L \cdot \frac{l_{OC}}{2} + 12 \cdot E_m \cdot I_Q \cdot \frac{h_{OC}}{l_{OC}^3} \quad (5.11)$$

The following now applies for the components of the draw-in force:

- from friction of the liner in the old pipe and on the ground (coefficient μ_G)

$$Z_g \cong \bar{g}_L \cdot L \cdot (\mu_G \cdot \cos\varphi_G \pm \sin\varphi_G) \quad (5.12a)$$

+ with draw-in against the gradient,
- with draw-in with the gradient
L = length of the pipe string

- from friction at the guide rollers and the reduction machine (rolling friction, coefficient μ_R)

$$Z_M = (\bar{A}_1 + A_1 + A_2 + \bar{A}_2) \cdot \mu_R \quad (5.12b)$$

- with bending of the sewer section with the included angle ß

$$Z_ß = Z \cdot e^{\mu_G ß} \quad (5.12c)$$

with Z = tensile force up to the bend

and the resultant tensile force

$$\Sigma Z = Z_g + Z_M + Z_ß \quad (5.12d)$$

5.1.2.2 Stresses

The maximum tensile force, however no bending moment, occurs at the *pulling head*. With the welding factor α_W , the net cross-section $A_{Q,n}$ (after discounting screw holes) and $E_T \geq E_C$ the calculated stress results as follows:

$$\sigma_T = \frac{\sum Z}{A_{Q,n} \cdot \alpha_w} \quad (5.13)$$

On the *old pipe (*1) the tensile stresses on the liner

$$\sigma_z = \frac{\sum Z}{A_Q} + \frac{M_{1,h} + M_{1,g}}{W_Q} \tag{5.14a}$$

with $W_Q = \frac{2 \cdot I_Q}{d_{L,e}}$, I_Q in accordance with EQN. (5,6b) and (5.14b)

A_Q in accordance with Eqn, (5.7d)

and the compression stresses are determined.

$$\sigma_C = -\frac{M_{1,h} + M_{1,g}}{W_Q} \quad \text{(without } \sigma \text{ from Z)} \tag{514c}$$

For the calculation of the stresses at the *edge of the construction trench* (2) the tensile forces as a result of friction may be deducted from A_1 and $\bar{A}_1$. Thus the eqns. (5.14a-c) apply analogously if the index 1 is replaced by 2.

5.1.2.3 Elongation Detection

Using the tensile stresses from Eqn (5.13) and (5.14a) the elongations are

$$\varepsilon_T = \frac{\sigma_z}{E_z} \cdot 100\% \leq \varepsilon_{perm} \tag{5.15}$$

and using the compression stresses from Eqn. (5.14c) the compression sets are

$$\varepsilon_C = \frac{\sigma_C}{E_C} \cdot 100\% \leq \varepsilon_{b,perm} \tag{5.16}$$

For PE-HD with elongations ε_{perm} = 3%, with compression sets, due to the danger of buckling, $\varepsilon_{b,perm}$ according to Table 3.

5.1.3 Case 2: Free Support on Edge of Trench

The pipe string is drawn with clearance into the old pipe via a supporting trestle at the edge of the trench, comp. Fig. 3: In order to reduce the bending moment M_2 at the edge of the trench and to shorten the construction trench an additional support can be provided with the separation l_3.

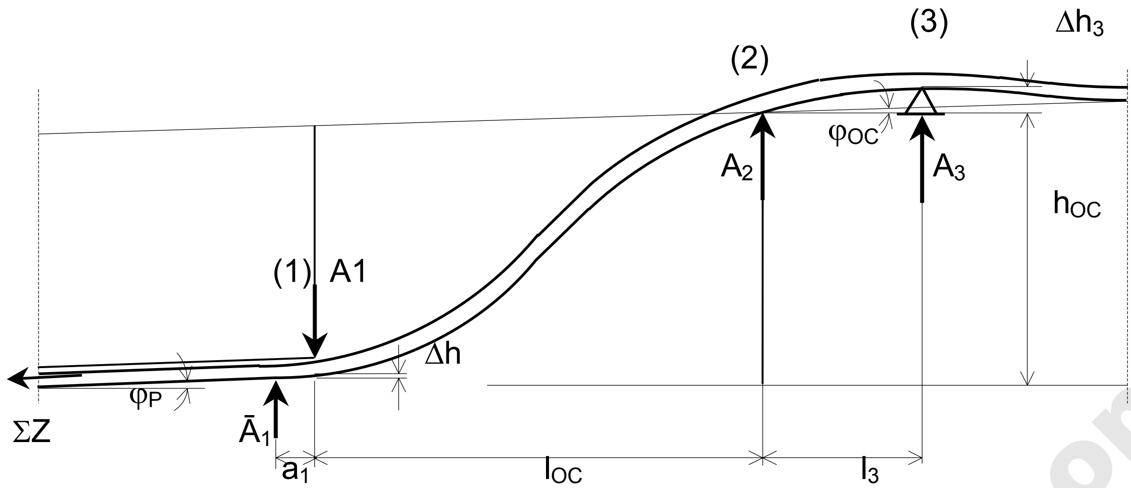

Fig. 3: Drawing-in process via the start trench, Case 2 (free support at trench edge, clearance Δh between liner and old pipe

For PE-HD pipes of pressure levels PN3.2, PN4, PN6 and PN10 without additional support (l_3 = 0) and $\varphi_P = \varphi_{OC} = 0$ the minimum lengths of the trench elated to $d_{L;e}$ and the bearing forces A_1 and A_2 related to $\bar{g}_L$ are tabulated in Appx. A1.

This gives the minimum length of the draw-in trench without further verification of elongation as:

$$\min l_{OC} = \min\left(\frac{l_{OC}}{d_{L,e}}\right) \cdot d_{L;e} \tag{5.17}$$

For the bearing forces A1 and A2 the following applies:

$$A_{1,2} = \left(\frac{A_{1,2}}{\bar{g}_L}\right) \cdot \bar{g}_L \tag{5.18}$$

For the determination of the tensile forces Z_g, Z_M and $Z_ß$ eqns. (5.12a) to (5,12d) apply accordingly. In the diagrams for min l_{OC} in Appx. A1 the components Z_g and Z_M are included. The effects of bends and the forces $Z_ß$ resulting from these must, if necessary, be determined separately.

5.2 Filling of the Annular Space

5.2.1 Preamble

Following the drawing-in of the pipe string or with short pipe lining the remaining annular space must be plugged with a suitable free-flowing special mortar, in particular with the presence of external water pressure. The following objectives for this are given in ATV Advisory Leaflet ATV-M 143E, Part 3, Sect. 6.1:

- fixing of the inliner
- prevention of penetration of soil and water
- creation of a defined bedding in the sewer
- even transfer of external loads
- prevention of dangerous gas bubbles.

The filling process represents a separate loading situation for the liner which is to be investigated. Various constraints can occur:

- lineal support of the invert (or the crown) with liners with high flexural strength
- areal support of the invert (or the crown) with unknown distribution of the reaction stresses (area $2\alpha_B$) with liners with low flexural strength
- support in two continuous or interrupted lines with the employment of spacers (angle $2\alpha_S$)
- special bedding with filling in partial steps.

The loads are made up from
- filling pressure
- possible existing overpressure (expanding filling materials)
- with larger sewer cross-sections dead-weight of the liner and
- possibly heat effects as a result of hardening.

With injecting, pressure limitation is absolutely necessary due to the danger of buckling of unbedded liners.

5.2.2 Sectional Measurements and Stress Detection

In accordance with Fig. 4, four load cases are to be overlapped with the filling of the annular gap in one step:

1. dead-weight $g_L = \gamma_L \cdot s_L$ of the liner wall in the direction of the circumference
2. external pressure $p_e = \gamma_F \cdot d_{L,a}$ through liquid filler
3. overpressure $p_o = \gamma_F \cdot (h_F - d_{L,e})$ through liquid filler with longitudinal slope of the sewer section
4. internal pressure $p_i = \gamma_w \cdot d_{L,i}$ through the filling of the liner with water

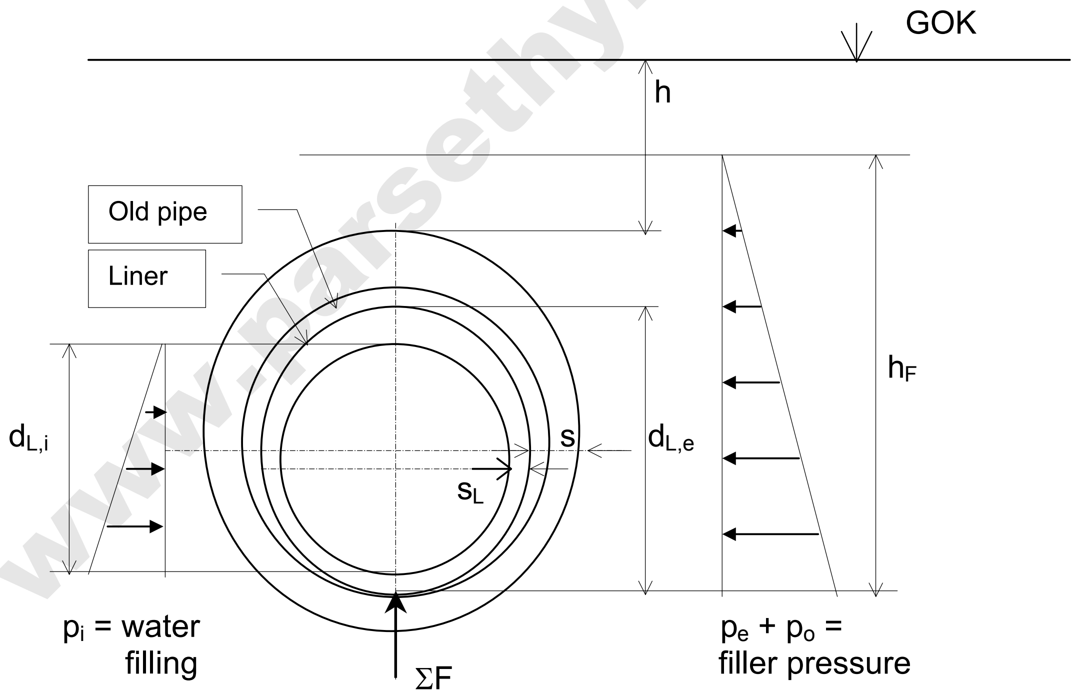

Fig. 4: Loading situation with filling of the annular gap. Case A (subsidence) and Support Case I (lineal support) are represented.

A *subsidence* (Case A) with support in the invert results with

$$\sum F = F_g + F_w - F_F = \gamma_L \cdot s_L \cdot 2r_L \cdot \pi + (\gamma_W \cdot d_{L,e}^2) \cdot \frac{\pi}{4} > 0 \qquad (5.19)$$

With $\sum F < 0$ a floatation up to the crown takes place Case B)[26)].

The support cases are differentiated:
- I = lineal support, with rigid liners ($\alpha_B = 0$)
- II/90° = stepped, over $2\alpha_B = 90°$ distributed support pressure (with flexible liners)
- III/60° = lineal support provided by two spacers with a separation of $2\alpha_A = 60°$ (with rigid and flexible liners)

[26)] This case is, according to ATV-M 143E, Part 3, not foreseen for operational reasons

The stress resultants are determined according to the following equations using the coefficients m and n.

Dead-weight:

$$M_g = m_g \cdot \gamma_L \cdot s_L \cdot r_L^2$$
$$N_g = n_g \cdot \gamma_L \cdot s_L \cdot r_L \qquad (5.20a,b)$$

variable external pressure (filler):

$$M_F = m_F \cdot \gamma'_F \cdot r_F^3$$
$$N_F = n_F \cdot \gamma'_F \cdot r_F^2 \qquad (5.21a,b)$$

with $\gamma'_F = \gamma'_F \cdot \left(\frac{d_{L,e}}{2r_L}\right)^2$ (5.21c)

to take into account the difference between the external diameter $d_{L,e}$ and the diameter of the middle line $2r_L$ of the liner.

With relieving effect M_F is dispensed with.

Constant external pressure (filler overpressure):

$$M_O = 0$$
$$N_O = -p_O \cdot r_{L,e} \qquad (5.22a,b)$$

Water filling:

$$M_w = m_w \cdot \gamma'_w \cdot r_L^3$$
$$N_w = n_w \cdot \gamma'_w \cdot r_L^2 \qquad (5.23a,b)$$

with $\gamma'_w = \gamma'_w \cdot \left(\frac{d_{L,i}}{2r_L}\right)^2$ (5.23c)

to take into account the difference between the internal diameter and the diameter of the middle line $2r_L$ of the liner.

With liners, which are not clearly flexible, the bedding angle $2\alpha_B$ is assumed as zero to be on the safe side. Alternatively, a precise calculation of all physical parameters, for example using a strut and joint program according to the second-order theory, can be carried out. For such a calculation the modulus of elasticity E (t, υ) of the liner is required which depends on the bonding temperature υ and the bonding time t up to the early strength of the filler material.

The tensile forces result using the Eqns. (6.17) and (6.18).

5.2.3 *Deformations*

Deformations resulting from the filling can be determined approximately assuming a lineal loading in the crown and the invert of the liner:

$$\Delta d_v \cong 0.1488 \cdot \frac{\sum F \cdot r_L^3}{E(t,\upsilon) \cdot I} = 0.1488 \cdot \frac{12 \cdot \sum F}{E(t,\upsilon)} \cdot \left(\frac{r_L}{s_L}\right)^3 \quad (5.24a)$$

$$\delta_v = \frac{\Delta d_v}{2 \cdot r_L} \cdot 100\% \quad (5.24b)$$

Calculations using the precise size of the bedding angle $2\alpha_B$ are possible with the aid of a rod and joint program.

5.2.4 *Stability Verification*

Due to the large gap the application of a circumferential bedding is not permitted. The buckling equation of the unbedded pipe under external pressure is

$$p_{e,crit} = 3.0 \cdot S_L \quad (5.25)$$

with $S_L = \frac{E(t,\upsilon) \cdot I}{r_L^3}$

and $I = \frac{1}{12} \cdot s_L^3$ with even-walled liners with homogenous wall structure

The influence of the lateral strain coefficient μ in the liner stiffness S_L is neglected on the safe side. Prestrains with unbedded pipes need not be taken into account as here they have only a small reducing effect.
The safety against buckling of the liner on filling the annular gap is

$$\gamma = \frac{p_{e,crit}}{p_{e,exist}} \geq \gamma_{nec} \quad (5.26)$$

with $p_{e,exist} = \frac{\sum N}{r_L}$ and γ_{nec} according to Table 4.

5.2.5 *Verifications for the Old Pipe*

The loading of the old pipe as a result of filler pressure is to be estimated. This applies in particular with old pipes with small or no existing ring tensile strength, for example brickwork, old pipes with longitudinal cracks and cross-sections which deviate from the circular.

6 Verification for Service Conditions

6.1 Limitation for Cases in Which the Static Verification Can be Dispense with

A static verification with liners up to DN 250 with materials according to Table 2 may be dispensed with if the following conditions exist *concurrently*:

- no groundwater (p_e = 0)
- no internal pressure
- Old Pipe Condition **I**
- no danger of the occurrence of water at the shafts.

6.2 Stability of the Old Pipe-Soil System (Old Pipe Conditions II and III)

The verification of the stability of the old pipe-soil system for the Old Pipe Condition **II** and, if necessary, **III** in accordance with Figs. 1b and 1c is possible with the aid of the load displacement curves of the four bar linkage ring in accordance with Fig. 5. With this the following conditions are to be observed:

- the relationship between loading q_v and p_v (if necessary also for p_e) and the crown sag as reference deformation are derived on the *deformed system*.
- the distribution of the bedding reaction stresses q_h* - in deviation from ATV Standard ATV-A 127E - is to be assumed as *triangular* and *distributed over 90°.*
- the sum of the lateral earth pressure q_h and the reaction stresses q_h* is to be limited by 75 % of the *passive earth pressure*.

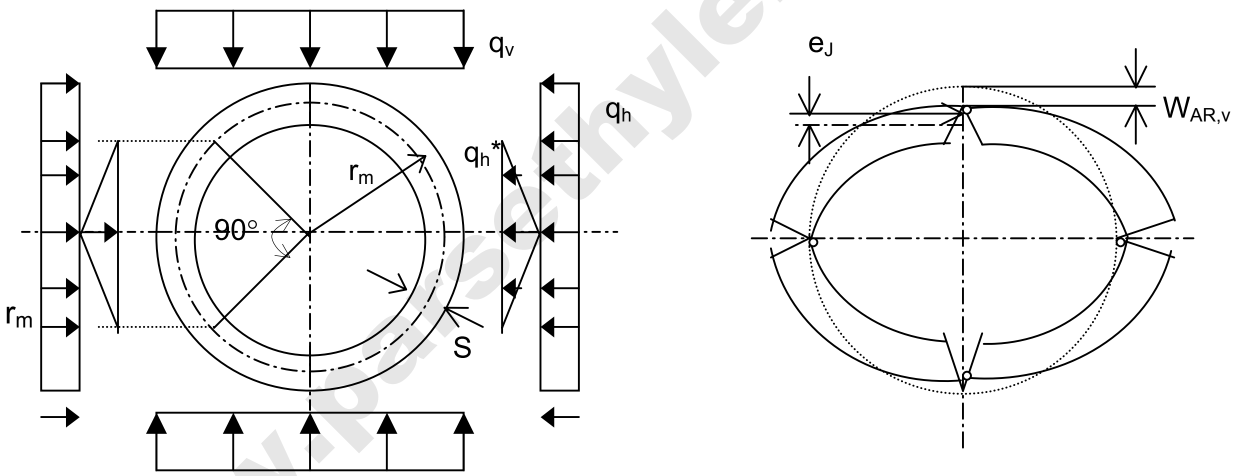

Fig. 5: System and loading of the old pipe-soil system from earth and traffic loads
a) undeformed sytem b) deformed system

The maximum values of the load displacement curves are the sought-after critical loadings $q_{v,crit}$, $p_{V,\ crit}$ and $p_{e,crit}$ of the system. They can be determined with the aid of the specific maximum loads in the diagrams in Appx. A6 and Eqns. (6.1) to (6.3). Eccentric linkages are accounted for globally using e_J =s/4 - with heavier damage of the pressure zones of the old pipe are, however, to be on the safe side, central linkages (e_J = 0) are to be applied[(27)].

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27) The relevant model of the old pipe-soil system according to Fig. 5a and of the liner-old pipe-soil system, according to Fig. 7c agrees completely with experimental results in [12]. Currently being checked by trials of the LGA Nürnberg [Germany].

For the load cases q_v, p_V and p_e the following critical loads apply with the aid of the maximum values of the curves in Appx. 6:

Case 1 mainly earth pressure q_v (without p_V):

$$q_{v,crit} = \max\left(\frac{q_v}{S_{Bh}}\right) \cdot S_{Bh} \qquad (6.1)$$

Case 2 mainly traffic loads p_V:

$$p_{V,crit} = \max\left(\frac{p_V}{S_{Bh}}\right) \cdot S_{Bh} \qquad (6.2)$$

Case 3 mainly external water pressure p_e (special case):

$$p_{e,crit} = \max\left(\frac{p_e}{S_{Bh}}\right) \cdot S_{Bh} \qquad (6.3)$$

The safety factor is determined as follows:

$$\gamma_I = \frac{q_{v,crit}}{q_v} \qquad (6.4)$$

For p_V and p_e Eqn. (6.4) applies analogously.

With simultaneous occurrence the safety factor of the old pipe-soil system is calculated approximately from the individual safety factors using the interaction equation

$$\gamma_1 = \frac{1}{q_v / q_{v,crit} + p_V / p_{V,crit} + p_e / p_{e,crit}} \qquad (6.5)$$

With safety factors $\gamma_I \geq \gamma_{I,nec}$ according to Table 4 is to be calculated according to Old Pipe Condition **II**, with safety factors $\gamma_I < \gamma_{I,nec}$ according to Old Pipe Condition **III**.

6.3 Calculation Models and Loading (Effects)

The loading (effects) is dependent on the existing condition of the old pipe and other conditions, which can occur during operation.

6.3.1 Old Pipe Conditions I and II[28)]

Due to the high pressure loading of the liner with external water pressure and the stability problems connected with this, *basic* prestrain (frequently also called imperfections) are to be determined.

28) If required, also Old Pipe Condition III with the presence of external water pressure

6.3.1.1 Prestrain (Imperfections)

With Old Pipe Condition I *local prestrain* of at least 2% of the liner radius[29)] according to Fig. 6a are to be assumed if, through inspection, it can be verified that no larger values exist.

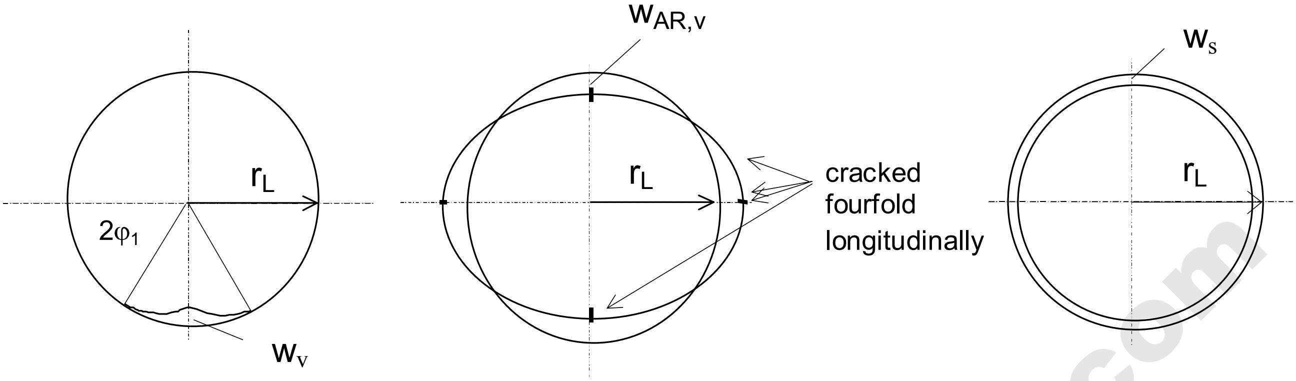


Fig. 6: Imperfections of the old pipe and the liner
a) locally limited prestrain w_v b) articulated ring prestrain $w_{AR,v}$ (ovalisation) c) gap formation w_s (annular gap)

If larger out-of-roundness exists after the smoothing of invert erosions, then this is to be considered through suitable application of prestrain based on Fig. 6a.

With Old Pipe Condition II additional articulated ring prestrain (ovalisation) of at least 3% of the liner radius according to Fig. 6b is to be assumed if, through inspection, it can be verified that no larger values exist.

The size of the gap formation according to Fig. 6c is to be determined with the aid of process checks and confirmed by outside monitoring. For the annular gap to be assumed the following minimum values apply:

- hose method 0.5% of the liner radius
- prestrained liner with later reformation, 2% of the liner radius.

6.3.1.2 Loading (Effects)

In accordance with the definitions according to Sect.3.2 and according to Fig.1, the following loading cases are possible with the presence of Old Pipe Conditions I and II:

- external water pressure effective on the surface of the liner
- internal pressure (underpressure, overpressure, possibly up to the surface of the ground)
- dead-weight (≥ DN 800)
- heat effects (cooling down or warming up)
- process dependent internal stresses[30)].

[29)] The locally limited prestrain of the depth of w_v (assumption 2%) is the supplementary imperfection for the consideration of geometric prestrain (assumption: 1.5%) and further faults in the liner and in the old pipe (assumption: 0.5%). The geometric prestrain according to Fig. 6a is matched to the lowest deformation figure belonging to the lowest buckling load. With the existence of accurate measured results of the old pipe profile the geometric prestrain can be reduced to1.5%of the measured value not, however, less than 0.5%. With this the complete local minimum prestrain is 1.0%.

Special loading conditions through external water pressure as a result of back-up and flooding events are to be considered using suitable application of loads. For this a short-term verification can be carried out in justified cases.

In order to ensure a sufficient minimum stiffness of the liner a supplementary water pressure of $h_{W,Inv} = d_e + 0.1$ m, however at least $h_{W,Inv} = 1.5$ m is to be assumed, independent of the groundwater level, and a long-term verification carried out for this.

6.3.1.3 Calculation Models

To simplify the calculation the three-dimensional structure (shell) may be reduced to a two-dimensional structure (flat distortion condition, plate). As a further simplification the liner can be calculated as rod and joint figure which is rigidly bedded in the old pipe, comp Fig. 7a,b.

With filler material with $E_F < 10{,}000$ N/mm^2 an elastic bedding is to replace the rigid bedding is to be applied.

According to the bedding of the liner in the old pipe with simultaneous presence of unavoidable prestrain and possible gap formation the external loads lead to higher compression forces N and bending moments M. Therefore a calculation according to the *second-order theory* (taking account of deformation in the equilibrium relationships) and the iterative improvement of the size of the contact area is necessary.

6.3.2 Old Pipe Condition III

6.3.2.1 Prestrain (Imperfections)

With Old Pipe Condition II *an articulated ring prestrain (ovalisation)* of 3% of the liner radius corresponding with Fig. 6b is to be assumed if, through inspection, no larger values exist.

With the verification for earth and traffic loads a gap formation is, on the safe side, to be neglected.

6.3.2.2 Loadings (Effects)

With old pipes which are cracked and the additional taking into account of the bearing effect of the soil, the following effects apply:

- earth and traffic loads, effective on the surface of the old pipe
- external water pressure effective on the surface of the liner
- internal pressure (underpressure, overpressure, possibly up to upper surface of the ground)
- dead-weight
- heat effects (cooling down or warming up).

[30)] The bearing load reducing influence of internal stresses with prestrained and reformed liners can not currently be quantified, first approaches can be used

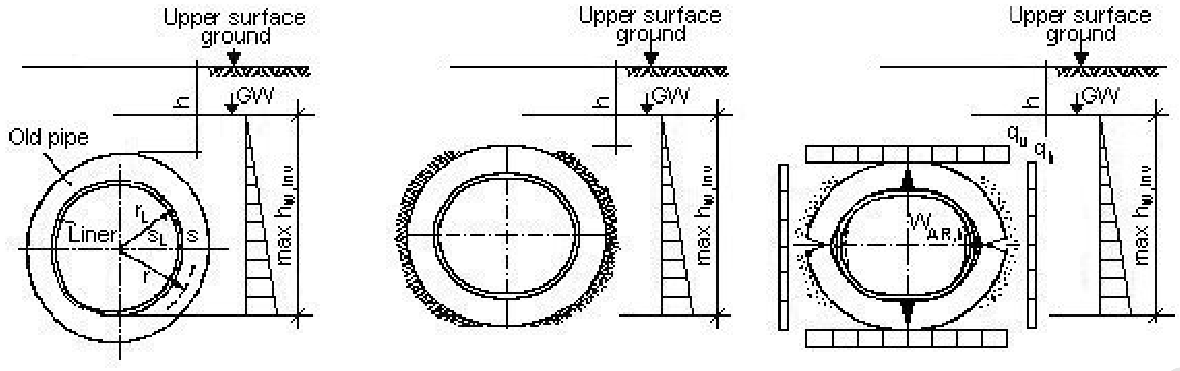


Fig. 7: Old pipe with liner
a) Old Pipe Condition I b) Old Pipe Condition II c) Old pipe condition III

6.3.2.3 Calculation Models

To calculate the strains of the liner both the following calculation models are possible:

- partial bedding model B_P (or partial continuity model C_P)
- full bedding model B_F (or full continuity model C_F)

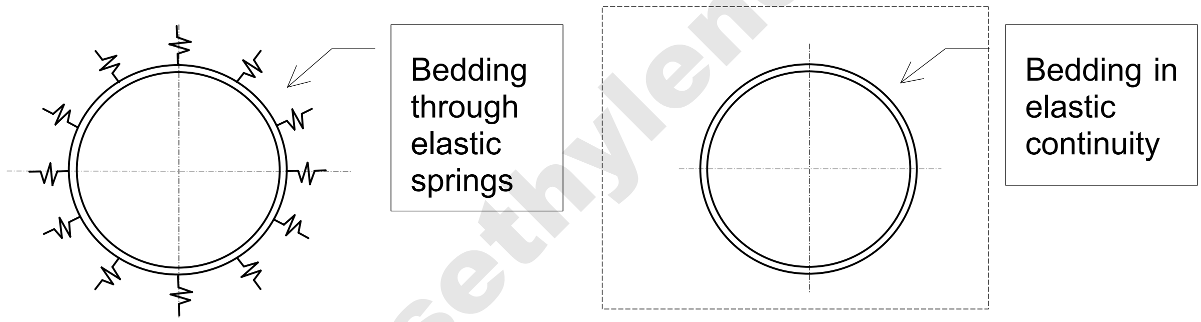


Fig. 8: Models with full bedding of the annulus
a) Bedding model B b) Continuity model C

With partial bedding and partial continuity models a part of the circumference remains unbedded (e.g. a 90° area in the crown). The models B_P (or C_P) provide greater strains on the liner and have to be applied with smaller earth covering and that is with

$$h < 3 \cdot d_e \quad \text{and} \quad h < 1.0 \text{ m} \tag{6.6}$$

The most unfavourable model B_P is based on the stress resultant coefficient tables m_q and n_q and the deformations γ_v in Appx. 5.

For larger coverings the models B_F and C_F may also be employed. Here attention is to be paid that, in the area of the crown of the old pipe, the total soil stresses do not undercut the following boundary values:

$$\min q_v = \lambda_P \cdot p_E \qquad \text{with } p_E = \lambda_S \cdot h \tag{6.7a,b}$$

With Old Pipe Condition III the liner is bedded in an old pipe which has been cracked four times longitudinally, comp. Fig 7c. The longitudinal cracks are idealised in the theoretical mode as moment joint with eccentricity e_J. e_J is set as part of the old pipe wall thickness s (as a rule $e_J = s/4$ applies).

Conditioned through the eccentric position of the joint the four joint ring of the longitudinally cracked old pipe is stretched and through this the liner is relieved. With poor condition of the old pipe (heavy corrosion, loss of wall thickness due to wear, formation of fragments etc.) smaller values down to $e_J = 0$ are to be assumed.

With underground pipes the bedding of the old pipe is assumed to be *constant radial bedding*. The calculation of the horizontal bedding stiffness S_{Bh} ensues from the modulus of elasticity E2 of the pipeline zone on the basis of ATV-DVWK Standard ATV-DVWK-A 127E:

$$S_{Bh} = 0.6 \cdot E_2 \qquad (6.8)$$

E_2 is, for example, to be determined from penetrometer soundings. To ensure the value of S_{Bh} the relaxed deformation of the longitudinally cracked old pipe can be used. For this S_{Bh} is calculated with the aid of the load-displacement curves in Appx. 6 (Diagrams A6/1 and A6/2), using the existing load q_v and the old pipe deformation.
The sum of the lateral earth pressure and the bedding reaction pressure $q_h + q_h^*$ may not exceed the following boundary values:

$$\max q_h = 0.75 \cdot K_p \cdot \lambda_S \cdot p_E$$
$$\text{with } K_p = \tan^2(45^\circ + \varphi'/2) \qquad (6.9a,b)$$

This limitation is then relevant if high lateral bedding forces are called upon for the stabilisation of the whole system. In Eqn. (6.9a) the factor 0.75 takes into account the increasing soil deformation before achieving the passive earth pressure.

6.3.2.4 Pressure Distribution at the Pipe Circumference

The stress situation over the pipe circumference is determined by the quantities q_v and q_h. The soil stresses, with Old Pipe Condition III (old pipe cracked four times longitudinally before rehabilitation), are reduced globally as follows:

$$\lambda_P = 0.75^{31)} \quad \text{and } \lambda_S = 1.08 \qquad (6.10a)$$

31) In the long-term an undisturbed old pipe-soil system can be assumed, thus the verification using an earth load

Note: The case (6.10b) may be verified using the short-term characteristic values of the liner. Additionally, a long-term verification is to be undertaken using λ_P and λ_S according to Eqn. (6.10a).

The traffic loads p_V are to be determined in accordance with ATV-DVWK Standard ATV-DVWK-A 127E, Diagrams D2 to D4. With this the following applies for the vertical load at the level of the pipe crown

$$q_v = \lambda_P (p_E + p_0) + p_V$$
$$\text{with } p_E \text{ according to Eqn. (6.7b)} \qquad (6.11a)$$

With the presence of groundwater the vertical load at the level of the pipe crown is determined in accordance with ATV-DVWK-A 127E, using the specific weight γ'_S of the soil under water:

$$q_v = \lambda_S \left[\gamma_S \cdot (h - h'_w) + \gamma'_S \cdot h'_w\right] + p_V \quad (6.11b)$$

The following applies for the horizontal earth pressure in the springer

$$q_h = K_2 \left(\lambda_S \cdot \gamma_S \cdot h + \gamma_S \cdot d_e / 2\right) + p_V$$
$$\text{with } K_2 \text{ in accordance with ATV-DVWK-A 127E} \quad (6.11c)$$

and with the presence of groundwater

$$q_h = K_2 \left[\lambda_S \cdot \gamma_S \cdot (h - h'_w) + \gamma'_S \cdot (h'_w + d_e / 2)\right] \quad (6.11d)$$

The lateral earth pressure coefficient is determined using q_v and q_h:

$$K_2' = \frac{q_h}{q_v} \quad (6.12)$$

For the external water pressure the following applies

$$p_e = \gamma_w \cdot \max h_{w,Inv} \quad (6.13)$$

with max $h_{w,Inv}$ = height of water above the invert of the liner. With, for example, calculations using the Finite Element Method, the buoyancy component is to be taken into account.

6.4 Stress Resultants, Stresses, Deformation

Below the stress resultants, stresses and deformation are examined only in the direction of the circumference - in the axial direction the loading distribution is assumed, as for the geometry, to be constant.

With deviations from this it is possible that special investigations are necessary. In many cases, however, an approximation on the safe side can be assumed as, with the relevant flat support model, the load distributing effect of the shell supporting framework is neglected. In opposition to this weakening of the liner wall due to the cutting out of the lateral connections without reinforcement using hat (domed) profiles does not lie on the safe side. Possible weakening through fabric seams or similar is to be taken into account through a longitudinal joint.

6.4.1 Stress Resultants with the Presence of Old Pipe Conditions I and II

The calculation models and procedures according to Sect. 6.3.2.1 lead to non-linear relationships between the loading p_e and the bending moment (as well as deformation). It thus results that the m- and δv coefficients are dependent on the load and the geometry.

The *bending moment coefficients* m_{pe} in Appx. 4 apply for **Old Pipe Condition I** (comp. Fig. 7a), for circular liners with constant wall thickness over the circumference, for external water pressure p_e and for assumed local prestrain and annular gap, comp. comments on page A4/1.

For the *bending moment coefficients* m_{pe} in Appx. 4 for **Old Pipe Condition II** (comp. Fig. 7b) an additional articulated ring prestrain (ovalisation) is applied, for more detail comp. comments on page A4/1.
For the normal force coefficient, to be on the safe side, the following can be applied:

n_{pe} = - 1.10 with verification of the compressive strain and

(6.14a,b)

n_{pe} = - 0.80 with verification of tensional strains

With deviating figures (other values for DN, E_L, w_v, $2\varphi_1$, $w_{AR,v}$, w_s) and with varying wall thicknesses and moments of inertia over the circumference and with cross-sections deviating from circular (oval profile, tapering profile etc.) other stress resultant coefficients apply. They are to be recalculated as a contact pressure problem in accordance with second-order theory.

Intermediate values, for example with other wall thicknesses s_L of the liner, interpolation may take place wit the aid of the diagrams in Appx. A4 as described on page A4/1.

Using the coefficients m_{pe} and n_{pe} the stress resultants as a result of external water pressure p_e for Old Pipe Conditions I and II are determined as follows:

$$M_{pe} = m_{pe} \cdot p_e \cdot r_L^2 \qquad (6.15a)$$

$$N_{pe} = n_{pe} \cdot p_e \; r_L \qquad (6.15b)$$

With internal pressure $p_i > 0, \; N_{pi} = + p_i \cdot r_L$ (6.15c)

The earth and traffic loads are allocated to the intact old pipe or old pipe-soil system respectively. With corrosion abrasion of the old pipe (reduction of the wall thickness by Δs) its stability is additionally to be checked in accordance with ATV-DVWK Standard AT-DVWK-A 127E.

6.4.2 Stress Resultants with the Presence of Old Pipe Condition III

In deviation to Standard ATV-DVWK-A 127E common stress resultant coefficients m_q and n_q are given for the soil stresses q_v, q_h and q_h* as, due to the necessary non-linear calculation the superposition principle no longer applies. The coefficients are dependent on the load q_v - a break in the values with increasing loading indicates a breakdown of stability.

The bending moment coefficients m_q and the normal force coefficients n_q in Appx. 5 apply for Old Pipe Condition III, for circular liners with constant wall thickness over the circumference, for earth and traffic loads q_v with K_2' = 0.20, for e_J = s/4 and for articulate ring prestrain of 0%, 3% and 6% of the liner radius (ovalisation), more detailed comments are given on page A5/1.

The stress resultants from vertical total loading q_v with simultaneous effect of q_h and q_h* are calculated using the following equations:

$$M_q = m_q \cdot q_v \cdot r_L^2 \qquad (6.16a)$$

$$N_q = n_q \cdot q_v \cdot r_L \text{ [32)]} \qquad (6.16b)$$

With internal pressure p_i > 0 Eqn. (6.15c) applies.

6.4.3 Stresses

Using the stress resultants determined in Sects. 6.4.1 and 6.4.2, the strains in the inner and outer edge fibres of the liner are calculated as

$$\sigma_i = \frac{N}{A} + \alpha_{ki} \cdot \frac{M}{W_i} \tag{6.17a}$$

$$\sigma_e = \frac{N}{A} + \alpha_{ke} \cdot \frac{M}{W_e} \tag{6.17b}$$

using the correction factors

$$\alpha_{ki} = 1 + \frac{1}{3} \cdot \frac{s_L}{r_L} \quad \text{and} \quad \alpha_{ke} = 1 - \frac{1}{3} \cdot \frac{s_L}{r_L} \tag{6.18a,b}$$

to take account of the bending of the liner wall.

Eqns. (6.17a,b) and in approximation also Eqn. (6.18a,b) apply for smooth walled and profiled liners the cross-section values are

$$A = 1 \cdot s_L \quad [\text{mm}^2/\text{mm}] \tag{6.19a}$$

$$W = W_i = W_e = \frac{1\, s_L^2}{6} \quad [\text{mm}^2/\text{mm}] \tag{6.19b}$$

A and W are related to 1 mm pipe length. Analogously this applies for the stress resultants N and M to be applied in Eqns. (6.17a,b)

[32)] The normal force coefficients according to Appx. 5 apply only for the case that longitudinal cracks in the old pipe are not opened up through internal pressures from assembly, i.e. the contact of parts of the old pipe in the longitudinal cracks must remain. Otherwise higher coefficients n_q than in Appx. 5 result.

6.4.4 Elongation

With materials for which elongations at rupture ε_R are given, the extreme fibre limiting strains are determined from the stresses as follows:

$$\varepsilon = \frac{\sigma}{E} \tag{6.19c}$$

6.4.5 Deformation

The elastic elongation $\delta_{v,el}$ for the Old Pipe Conditions I and II can be taken directly or interpolated from Appx. A4, Diagrams A4/7-12, for the cases named in Sect. 6.4.1.

For Old Pipe Condition III the elastic deformation in accordance with Appx. A5, Diagrams A5.1/9-10 and A5.2/9-10 applies.

The following quantities are to be added to the elastic deformation $\delta_{v,el}$: the stressless prestrain w_v to 50% as it occurs in the invert only, and with Old Pipe Conditions II and III the articulated ring prestrain $w_{AR,v}$ (ovalisation) to 100%.

$$\delta_v = \delta_{v,el} + \left(\frac{w_v}{2} + w_{AR,v}\right) \cdot \frac{100\%}{r_L} \qquad (6.20)$$

A possible formation of a gap (constant annular gap w_s) is not to be taken into account in Eqn. (6.20). The quantity w_s is, however, of significance for the hydraulic dimensioning. The reduction of the pipe cross-section from w_s is

$$\Delta A(w_s) = \frac{2 \cdot w_s}{r_L} \text{ in } \% \qquad (6.21)$$

To this still come reductions for the liner wall thickness s_L and the thickness of a possible filler.

6.5 Dimensioning

6.5.1 Stress Detection (Long-term, if Required also Short-term

The stresses or strains in the outer fibres determined in the service condition in accordance with Sect. 6.4 are to be compared with the arithmetic values σ_{bT}, σ_{bC} and ε_P for long-term conditions from Table 2. With the assumption of crack formation *after* the lining the greater *short-term* flexural strengths can be assumed. The existing safety coefficients from the relationship bending tensile stresses, compression stresses and the elongations

$$\gamma_{bT} = \frac{\sigma_{bT}}{\sigma} \text{ or } \frac{\varepsilon_P}{\varepsilon} \geq \gamma_{nec} \quad \text{for tensile stresses} \qquad (6.22a)$$

$$\gamma_{bC} = \frac{\sigma_{bC}}{\sigma} \text{ or } \frac{\varepsilon_P}{\varepsilon} \geq \gamma_{nec} \quad \text{for compressive strains} \qquad (6.22b)$$

with γ_{nec} according to Table 4.

With the mainly tensile stresses (high internal pressure) and omission of the supporting effect of the old pipe (large gap, Old Pipe Condition II or III), the tensile strength σ_T is to be used in place of the bending tensile strength σ_{bT} in Eqn. (6.22a).

If earth and traffic loads q_v occur simultaneously as well as external water pressure p_e with the presence of Old Pipe Condition III, the stresses can be superimposed as follows[33]:

$$\left(\frac{\gamma_{qv,nec} \cdot \sigma_{qv}}{\sigma_P}\right)^{2.0} + \left(\frac{\gamma_{pe,nec} \cdot \sigma_{pe}}{\sigma_P}\right)^{1.0} \leq 1 \qquad (6.22c)$$

The necessary level of safety for q_v and p_e in the numerators of Eqn. (6.22c) are to be taken from Table 4. For the strengths σ_P in the denominators with positive stresses in the numerator the bending tensile strength σ_{bT} is to be applied and with negative stresses the bending compressive strength σ_{bC}.

6.5.2 Stress Detection (Long-term)

The vertical change of diameter according to Sect. 6.4 is to be compared with the permitted value δ_{perm}, without taking into account a possibly constant annular gap. For the long-term verification $\delta_v \leq 10\%$ applies as reference value for the deformation of the old pipe and the liner together. For pipes under railway tracks the special conditions of the corresponding rail track company are to be taken into account.

6.5.3 *Stability Verification (Long-term*

The verification of stability serves for the determination of the safety distance between the elastic snap-through load of the liner and the existing loading. With **Old Pipe Conditions I and II** the verification is necessary for such effects which create considerable compressive forces in the liner wall, for example:

- external water pressure
- if necessary temperature changes
- dead-weight (with large nominal widths).

With **Old Pipe Condition III** there are additionally

- earth and traffic loads.

6.5.3.1 *External Water Pressure p_e/Internal Pressure p_i*

With exclusive external water pressure or internal pressure p_i < 1 bar, the following applies for liners with circular cross-section

$$p_{e,crit} = \kappa_{v,s} \cdot \alpha_{ST} \cdot S_L \tag{6.23}$$

[33] With the interaction equation it is taken into account approximately that, with a shortening of the circumference of the liner due to external water pressure the strains from earth and traffic loads are reduced.

with the snap-through coefficient $\alpha_{ST} = 2.62 \cdot \left(\frac{r_L}{s_L}\right)^{0.8}$ (6.24)

with the reduction factor for prestrain and gap formation (imperfections)

$$\kappa_{v,s} \cong \kappa_v \cdot \kappa_{AR,v} \cdot \kappa_s \tag{6.25}$$

with
- κ_v in accordance with Diagram D1 for local prestrain w_v according to Fig. 6a
- $\kappa_{AR,v}$ in accordance with Diagram D2 for articulated ring prestrain $w_{AR,v}$ according to Fig. 6b (Old Pipe Conditions II and III only; Old Pipe Condition I $\kappa_{AR,v} = 1$)
- κ_s in accordance with Diagram D3 for gap formation w_s according to Fig. 6c

κ_{vas} in Eqn. (6.25) can alternatively also be determined according to second-order theory with the joint application of prestrain *and* gap formation.
For the long-term pipe stiffness of the liner the following applies:

$$S_L = \frac{(EI)_L}{r_L^3} \quad \text{for profiled liners} \tag{6.26a}$$

$$S_L = \frac{E_L}{12} \cdot \left(\frac{s_L}{r_L}\right)^3 \quad \text{for smooth walled liners with homogenous wall structure} \tag{6.26b}$$

Diagram D1: Reduction factor κ_v for local prestrain

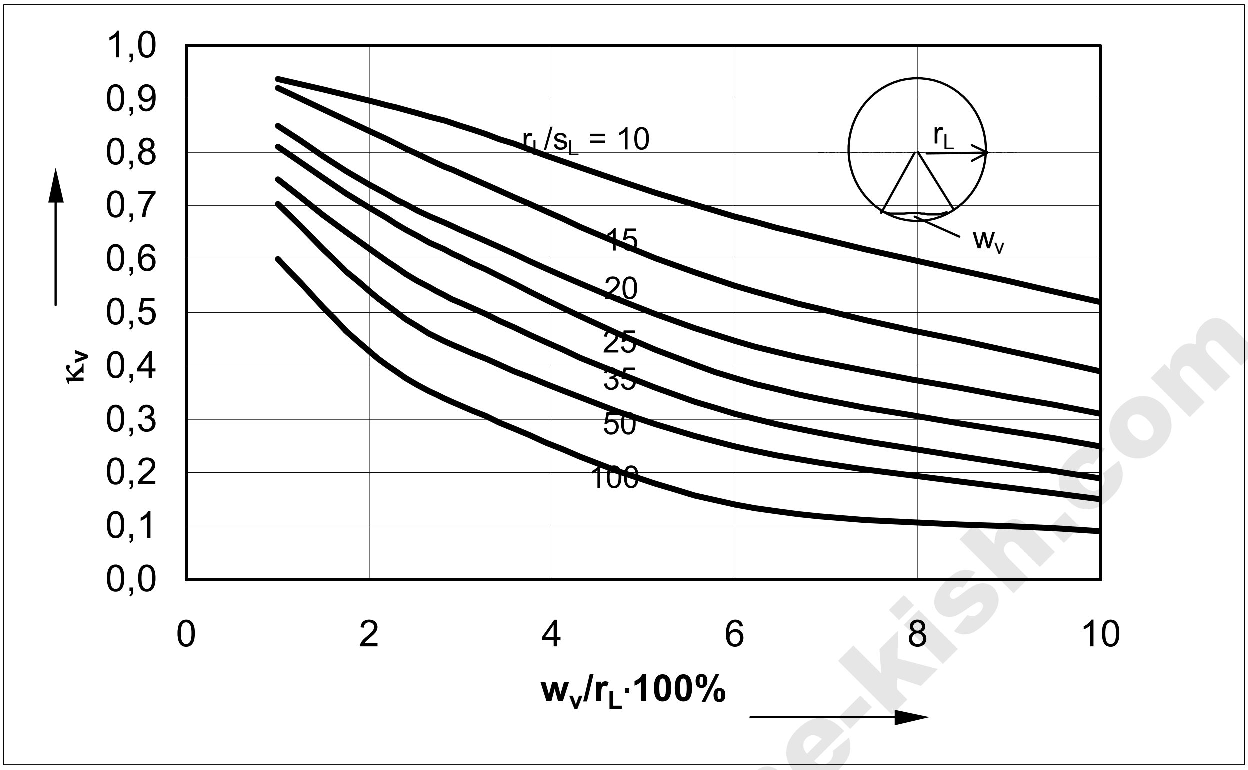


Diagram D2: Reduction factor κ_{ARv} for annular ring prestrain (ovalisation)

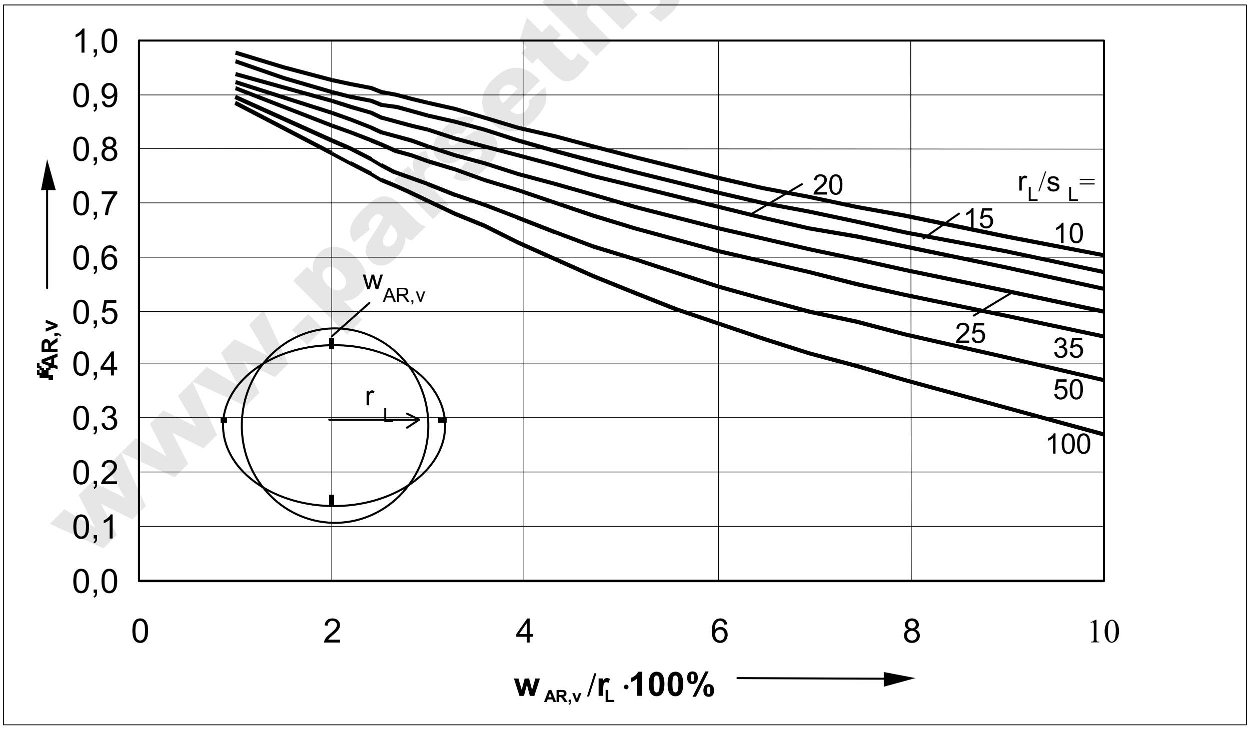
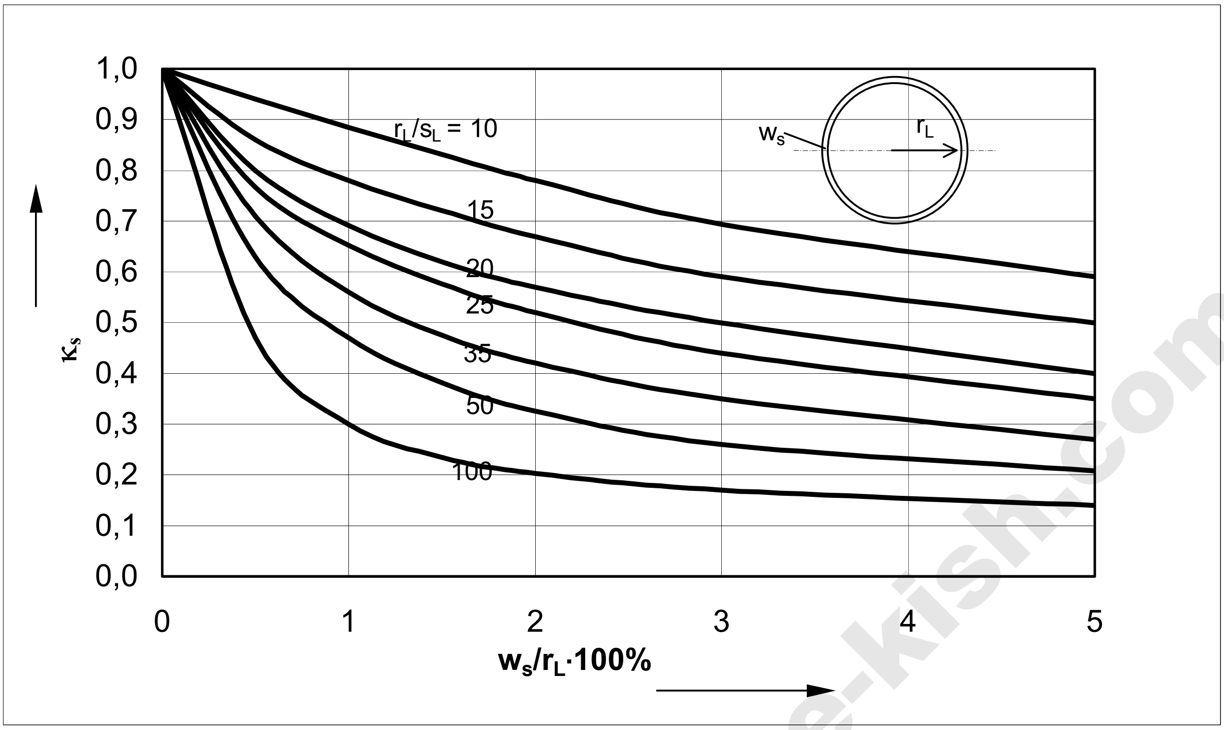


Diagram D3: Reduction factor κ_s for gap formation)



With Old Pipe Condition III the annular gap w_s to be assumed in accordance with 4.2.2 is to be increased by the component Δw_s from the articulated ring extension. For this the following applies

$$\Delta w_s = \frac{2}{\pi} \cdot \left(\frac{s}{2} + e_J \right) \cdot \delta_{v,el} \tag{6.27}$$

The linkage eccentricity can, as a rule, be assumed to be e_J = s/4, the elastic deformation component is determined according to Sect. 6.4.5.

With profiled pipes r_L/s_L in Eqn. (6.24) and in Diagrams D1 to D3 is to be replaced by

$$k^* = r_L \cdot \sqrt{\frac{A_L}{12 \cdot I_L}} \tag{6.28}$$

Eqns. (6.23) to (6.26) do not apply for profiles deviating from the circular - for these a separate calculation is to be carried out. A verification of the stability as stress verification II order with γ-times loads and application of imperfections based on Figs. 6a-c is permitted. Here non-circular profiles the local prestrain must be so applied that *it is similar to the inherent value of the associated buckling problem*.

The external water pressure p_e is the hydrostatic pressure referred to the invert of the liner in accordance with Eqn. (6.13). With this the verification against snap-through follows

$$\gamma_I = \frac{p_{e,crit}}{p_e} \geq \gamma_{nec} \quad \text{with } \gamma_{nec} \text{ in accordance with Table 4} \tag{6.29}$$

With internal vacuum (underpressure) (e.g, with water hammering in pressure pipes) the denominator of Eqn. (6.29) is to be replaced by p_i. If necessary p_e and p_i are to be taken into account together.

6.5.3.2 Change of Temperature $\Delta\upsilon$

With the effect of *cooling* on the liner, the gap appearing between liner and old pipe

$$w_s(\Delta\upsilon < 0) = \varepsilon(\Delta\upsilon < 0) \cdot \alpha_t \cdot |\Delta\upsilon| \cdot r_L \quad (6.30)$$

is to be calculated and, with the verification for external pressure/internal pressure, is to be added to an existing gap, comp. Eqn. (6.25).

With *heating* of the liner the critical contact pressure between liner and old pipe is

$$p_{\upsilon,crit} = \alpha_{\upsilon,min} \cdot S_L \quad (6.31)$$

with the snap-through coefficient (minimum of the load-displacement curve)

$$\alpha_{\upsilon,min} = 6.72 \cdot \left(\frac{r_L}{s_L}\right)^{0.8} \quad (6.32)$$

and the pipe stiffness S_L of the liner in accordance with Eqn. (6.26).

The contact pressure created by heating is

$$p_\upsilon = \alpha_t \cdot \Delta\upsilon \cdot E_L(\upsilon) \cdot \frac{s_L}{r_L} \quad (6.33)$$

If necessary the temperature dependent E-modulus of the liner material is to be applied.

Thus the verification to counter snap-through follows as

$$\gamma_I = \frac{p_{\upsilon,crit}}{p_\upsilon} \geq \gamma_{nec} \quad \text{with } \gamma_{nec} \text{ in accordance with Table 4.} \quad (6.34)$$

6.5.3.3 Dead-Weight

Snap-through of liners under dead-weight is of significance only with larger nominal widths (dependent also on E_L). With this, anchored systems, for example at the crown, are frequently employed.

For systems which are not anchored the following applies with *gap-free* installation:

$$g_{L,crit} \cong \kappa_v \cdot \alpha_{ST}\ S_L \quad (6.35)$$

with the snap-through coefficient

$$\alpha_{ST} \cong 2.03 \cdot \left(\frac{r_L}{s_L}\right)^{0.8} \quad (6.36)$$

with the reduction factor κ_v for prestrain according to Diagrams D1 and D2 and with the pipe stiffness of the liner in accordance with Eqn. (6.26)

Thus the verification to counter snap-through at the crown follows as

$$\gamma_I = \frac{g_{L,crit}}{g_L} \geq \gamma_{nec} \quad \text{with } \gamma_{nec} \text{ in accordance with Table 4.} \quad (6.37)$$

If necessary a verification for the maximum compressive force in the invert is to be carried out.

With anchored systems and with installation which is not gap-free, verification in accordance with second-order theory is to be carried out. With this the influence of prestrain on the following positions must be taken into account:

- at the crown = position with small compressive force but maximum gap width as a result of circumference shortening of the liner
- at the invert = position with maximum compressive force, however without gap formation before snap-through
- with oval profiles at the sides with small bending.
- with partial lining of the gas space which is anchored at the area of the invert, the slippage and/or resilience of the bonding agent, which is *not* included in Eqn. (6.35), is to be taken into account.

6.5.3.4 Earth and Traffic Loads

With Old Pipe Condition III the stability for the load case earth and traffic loads is also to be examined. A two-axis symmetry applies, comp. Fig. 1c.

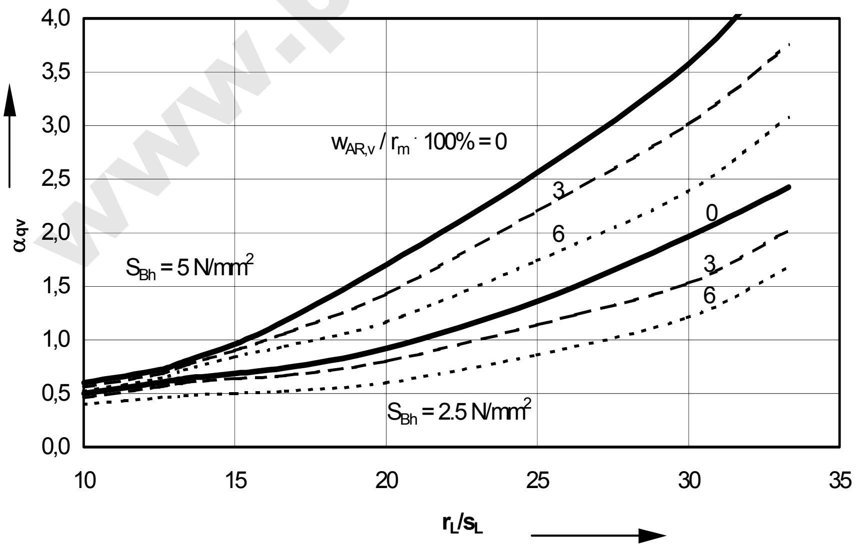
The limiting values for which no convergence can be achieved with the determination of the coefficients m_q and n_q are defined as critical loads. The following critical loads derive according to Diagram D4 using the coefficient α_{qv}

$$q_{v,crit} = 167 \cdot \alpha_{qv} \cdot \left(\frac{s_L}{r_L}\right)^{2.2} \quad \text{in N/mm}^2 \tag{6.38}$$

As already for m_q and n_q the validity limits in the explanations to Appx. A5, page A5/1 also apply for α_{qv}. With this the verification to counter the reaching of the stability limits follows as

$$\gamma_I = \frac{q_{v,crit}}{q_v} \geq \gamma_{nec} \quad \text{with } \gamma_{nec} \text{ in accordance with Table 4.} \qquad (6.39$$

Diagram D4: Coefficient α_{qv} of the critical vertical loading $q_{v,crit}$



For the cases deviating from the parameters according to page A5/1 it is also permitted to carry out verification as stress verification using γ-times the loads in accordance with second-order theory. The safety factors in the stability verification are

$$\gamma_I = \frac{\sigma_{bT}}{\sigma} \text{ or } \frac{\varepsilon_P}{\varepsilon} \quad \text{for tensile stresses} \qquad (6.40a)$$

$$\gamma_I = \frac{\sigma_{bC}}{\sigma} \text{ or } \frac{\varepsilon_P}{\varepsilon} \quad \text{for compressive stresses} \qquad (6.40b)$$

6.5.3.5 Interaction

If earth and traffic loads q_v as well as external water pressure p_e occur simultaneously with the presence of Old Pipe Condition III, then the following interaction relationship can be used as an approximation[34]:

$$\left(\frac{\gamma_{qv,nec} \cdot q_v}{q_{v,crit}}\right)^{2.0} + \left(\frac{\lambda_{pe,nec} \cdot p_e}{p_{e,crit}}\right)^{1.0} \leq 1 \qquad (6.41)$$

The necessary safety for q_v and p_e in the numerator of Eqn. (6.41) are to be taken from Table 4. The critical loads in the numerator are determined using Eqns. (6.38) and (6.23). Here $p_{e,crit}$ is to be calculated without employment of an annular gap (w_s according to Fig. 6c).

6.6 Cases for which No Coefficients are Available

Cases in which no coefficients for the bending moments, normal forces, deformation and critical loading $p_{e,crit}$ are available, are to be investigated though a separate calculation as contact pressure problem according to second-order theory.

With this the details under 6.3.2.3 apply for the possible calculation model and loading. In the case of a simultaneous occurrence of earth and traffic loads as well as external water pressure with Old Pipe Condition III, the buoyancy effect of the external water pressure is to be taken into account in the common support model. the system is therefore asymmetrical to the horizontal axis.

6.7 Observations on Oval and Other Cross-sections

6.7.1 Imperfections with Normal Oval Cross-section

For the load case of external water pressure (Old Pipe Conditions I and III) the locally limited prestrain in the middle of the flat area is to be arranged on one side inwards. The minimum depth of this prestrain is to be set at 0.5 % of r_k[35] (r_k =bending radius in the flat area, see Fig. 9).

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[34] Comp. footnote 33

[35] The locally limited prestrain with the depth w_v (assumption: 0.5 % of r_K) the substitute imperfection for the recording of geometric prestrain (assumption: 0.3 % of r_K) and further faults in the liner and in the old pipe (assumption: 2 % of r_K). The geometric prestrain according to Fig. 9 is matched to the asymmetrical prestrain figure belonging to the lowest buckling load. With the presence of precise measured results of the old pipe profile the geometric prestrain of 0.3 % can be reduced to the measured value, however to not less than 1 %. Thus the total local prestrain is 0.3 % of r_K. With the calculation attention is to be paid that, using this approach, no unsafe symmetrical conditions are calculated [7].

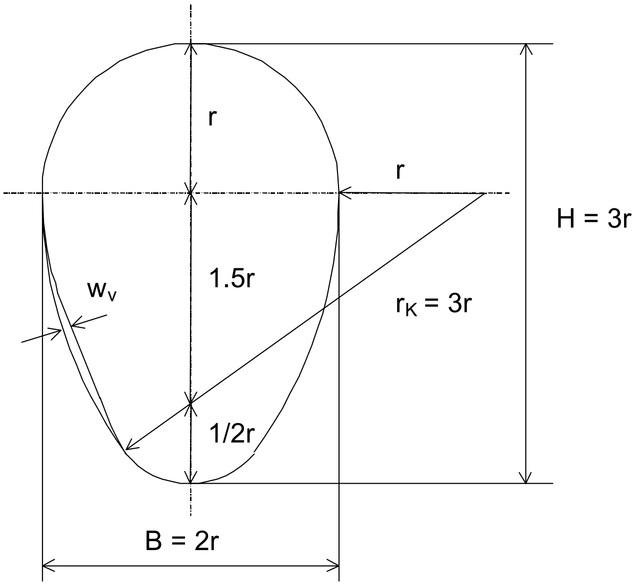

Fig. 9: Normal oval cross-section, for example i.a.w. DIN 4263 with prestrain at the left-hand springer

In Old Pipe Conditions II and III an additional articulated ring prestrain (ovalisation) of the crown inwards is to be assumed. 3% of the crown radius is to be assumed if it can be subsequently verified through inspection that no larger values exist.

The size of a gap formation (annular gap) with Old Pipe Conditions I and II is to be determined through measurement; with hose linings 0.5 % of the crown radius is recommended. With verification for earth and traffic loads (Old Pipe Condition III) is, on the other hand, a gap formation is to be neglected to be on the safe side.

6.7.2 Other Profiles

With cross-sections deviating from circular and normal oval profiles, theoretical investigations of the reduction factors are to be carried out together with measurements of the imperfections in the old sewer for the reductions caused by the imperfections.

7 Safety Concept

Global safety coefficients based on ATV-DVWK Standard ATV-DVWK-A 127E are to be employed. The coefficients are to be taken from Table 4.

Table 4: Safety coefficients γ_{nec} for liners

Material	Old pipe condition	Loading	Failure through fracture $\gamma_{bT,nec}$ $\gamma_{bC,nec}$	Failure through instability $\gamma_{I,nec}$
Plastic Fibre cement	I to III	p_e, g_L	2.0	2.0
	I to III III	$\Delta\upsilon > 0$ q_v	1.5[36)]	1.5[34)]
Steel	I to III	all	1.5	2.0
Vitrified clay	I to III	all	2.2	-

[36)] The liner with temperature increases ($\Delta\upsilon > 0$) and with earth and traffic loads (qv) is in positive locking with the old pipe-soil system. In these cases the reduced safety factor can be applied

8 Standard Specifications

For rehabilitation through lining and assembly processes, in addition to the pipe material standard specifications given in ATV-DVWK Standard ATV-DVWK-A 127E, Table 3, the following standard specifications are to be observed:

ATV-M 143E	Inspection, repair, rehabilitation and replacement of sewers and drains, Part 1: Principles, Part 22: Optical inspection, Part 3: Relining, Part 5: General requirements on performance verification of relining processes, Part 6: Leak testing of existing earth covered sewers, drains and shafts using water, air overpressure and vacuum.
DIN EN 476	General requirements for components used in discharge pipes, drains and sewers.
DIN EN 752-5	Drain and sewer systems outside buildings - Part 5: Rehabilitation.
prEN 13566	Plastic pipes for the renovation of underground, pressureless drainage networks (Draft 1999), Part 1: General, Part 2: Close-fit lining, Part 4: On-site hardening hose lining

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Appendix A1
Determination of the trench length and the supporting forces with draw-in/push-in of the pipe string (Case 2)

Explanatory notes

1. Calculation model

The required draw-in trench length l_{OC} for Case 2 is determined:
free length at upper edge of trench, draw-in with clearance between old pipe and liner.
l_{OC} results from the following conditions:

- specified height difference h_{OC} = invert of old pipe up to deflection roller at the edge of the trench (minus clearance)
- maximum 3 % elongation or compression set in the liner
- maintenance of security against buckling of 1.5 for the pressed area of the liner.

2. Parameters

- HDPE liner PN 3.2 to PN 10
- d_e = 160 to 1000 mm
- stress-dependent moduli of elasticity:
  $E_{\sigma=3}$ = 970 n/mm^2 and $E_{\sigma=15}$ = 500 N/mm^2
- mean temperature υ = +20°C
- flat ground (φ_{OC} = 0) and negligible slope of old pipe (φ_P = 0)
- clearance of the liner in the old pipe $\Delta h = d_i - d_{L,e}$ = 0 to 0.5 · $d_{L.e}$
- no additional support.

3. Interpolation

Interpolation may be carried out between curves.

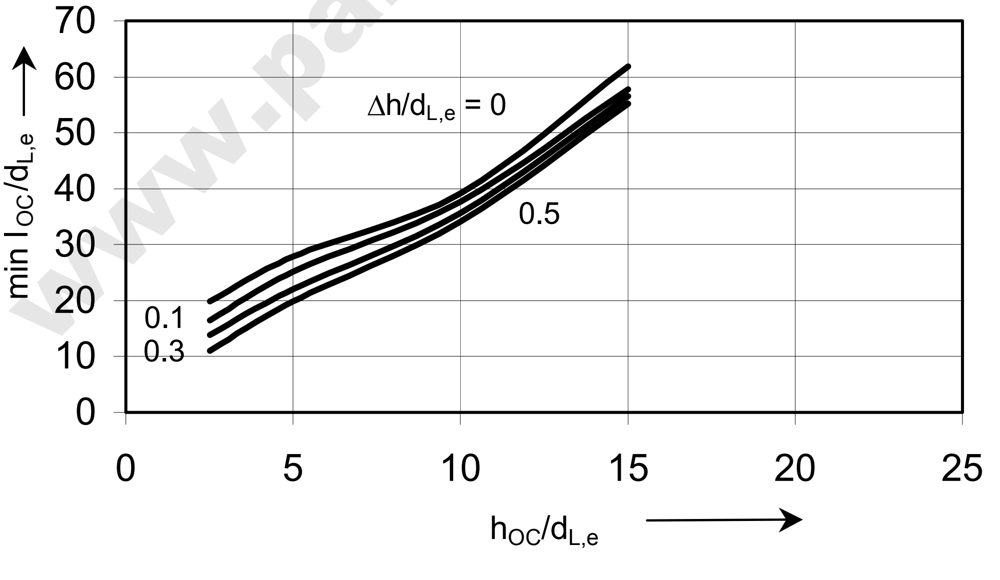


Diagram A1/1: **Required trench length l_{OC} for HDPE pipes PN 3.2 with draw-in into an old pipe (clearance $\Delta_h/d_{L,e}$)**

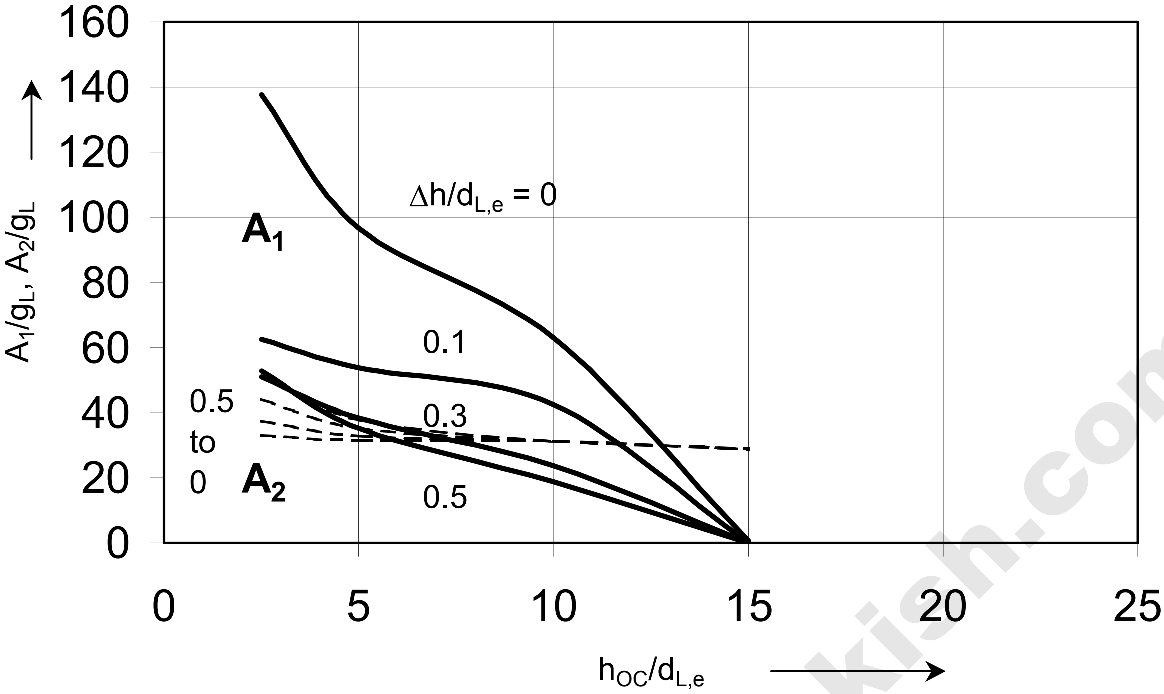


Diagram A1/2: **Support forces of HDPE pipes PN 3.2 at the old pipe (A_1) and at the edge of the trench (A_2) with draw-in into an old pipe (clearance $\Delta_h/d_{L,e}$)**

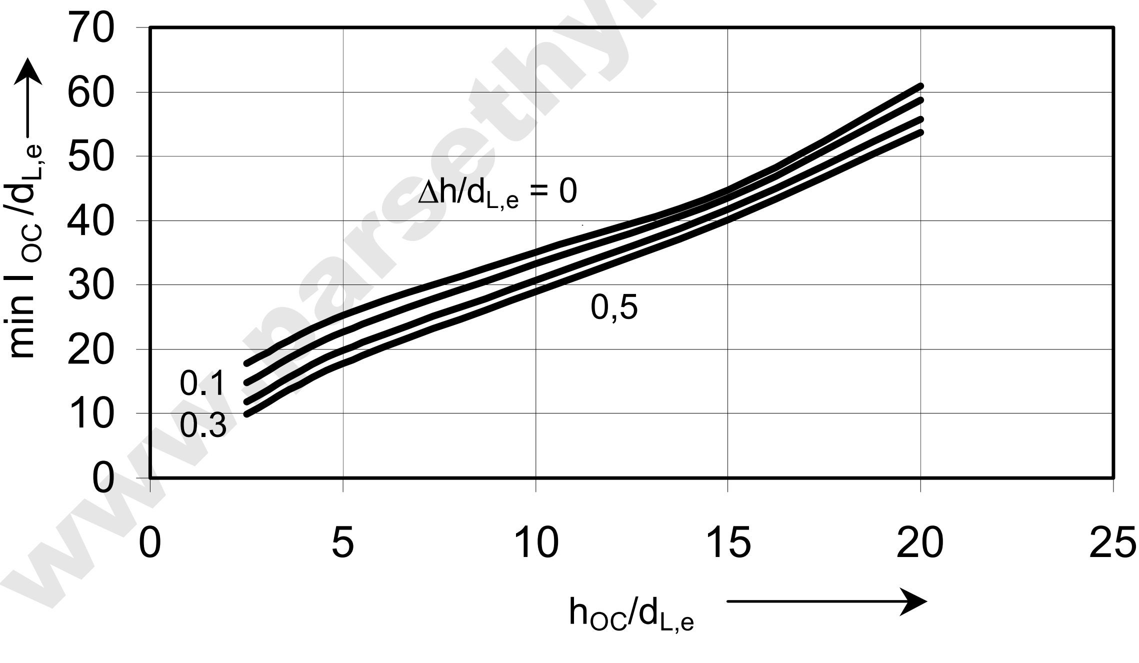


Diagram A1/3: **Required trench length l_{OC} for HDPE pipes PN 4 with draw-in into an old pipe (clearance $\Delta_h/d_{L,e}$)**

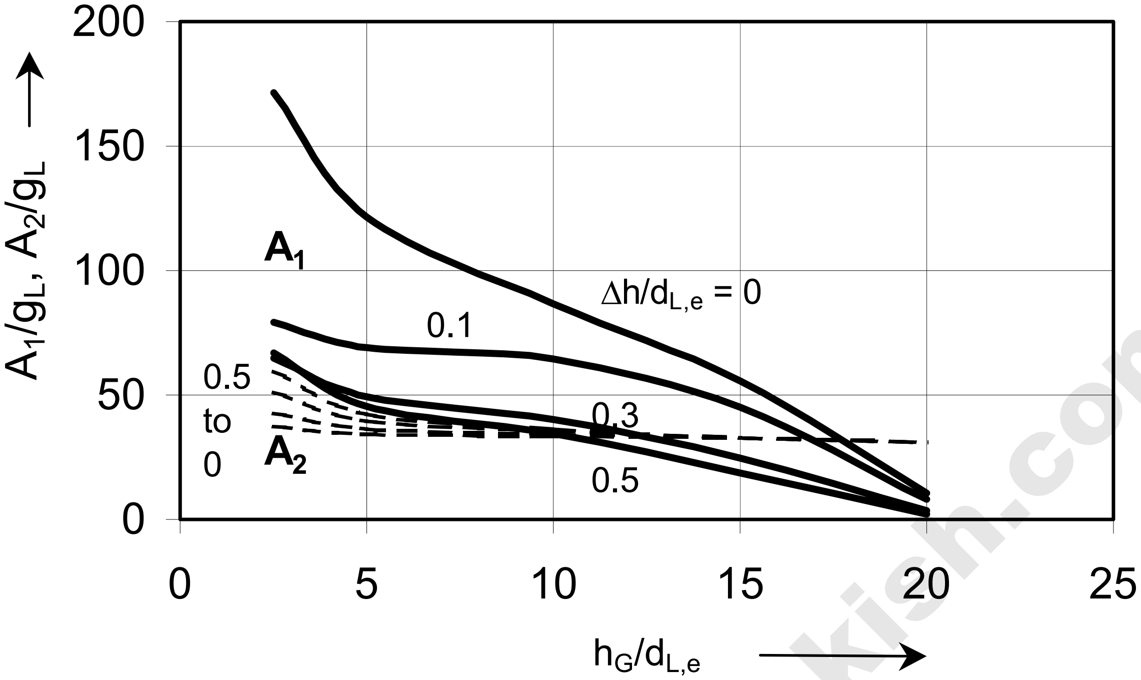


Diagram A1/4: **Support forces of HDPE pipes PN 4 at the old pipe (A_1) and at the edge of the trench (A_2) with draw-in into an old pipe (clearance $\Delta_h/d_{L,e}$)**

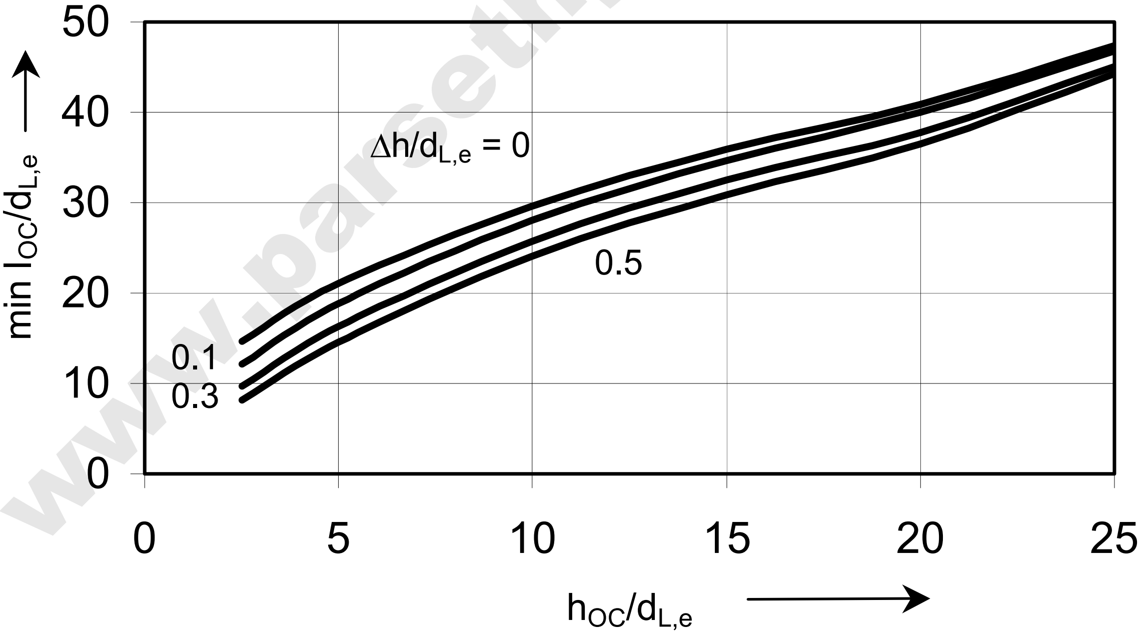


Diagram A1/5: **Required trench length l_{OC} for HDPE pipes PN 6 with draw-in into an old pipe (clearance $\Delta_h/d_{L,e}$)**

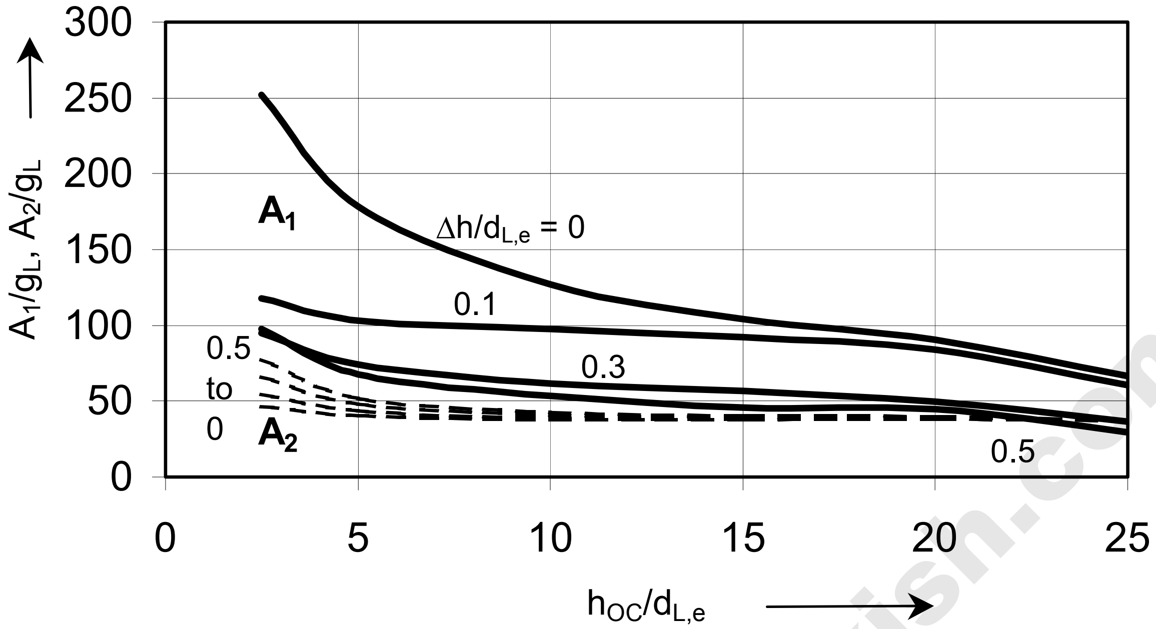


Diagram A1/6: **Support forces of HDPE pipes PN 6 at the old pipe (A_1) and at the edge of the trench (A_2) with draw-in into an old pipe (clearance $\Delta_h/d_{L,e}$)**

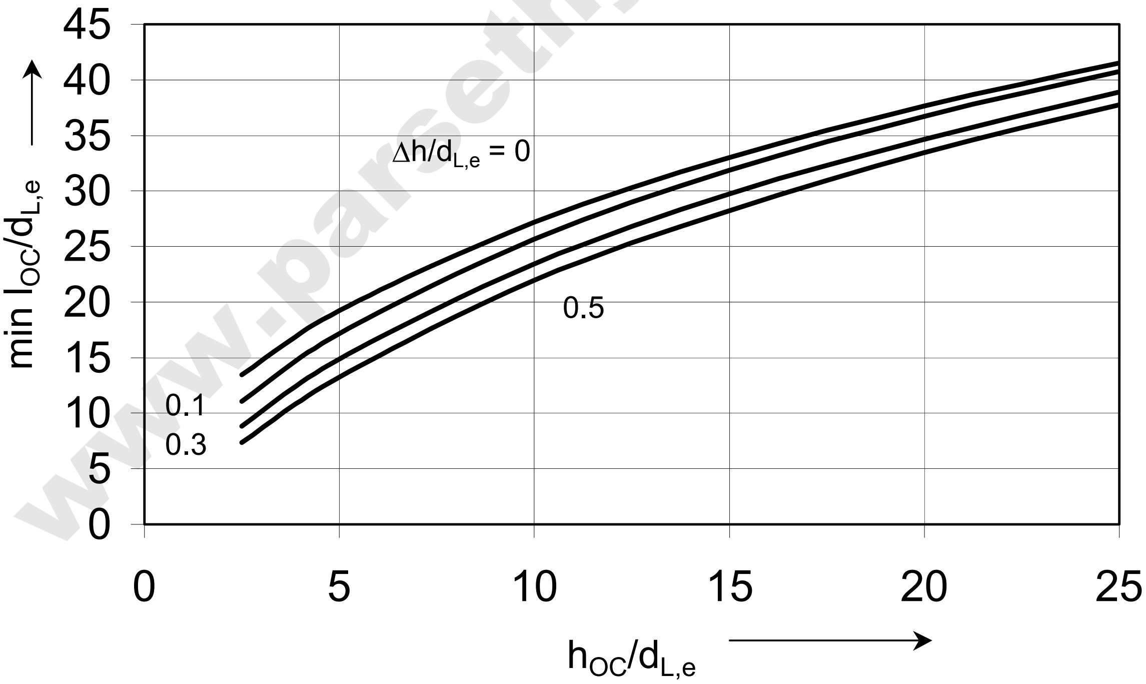


Diagram A1/7: **Required trench length l_{OC} for HDPE pipes PN 10 with draw-in into an old pipe (clearance $\Delta_h/d_{L,e}$)**

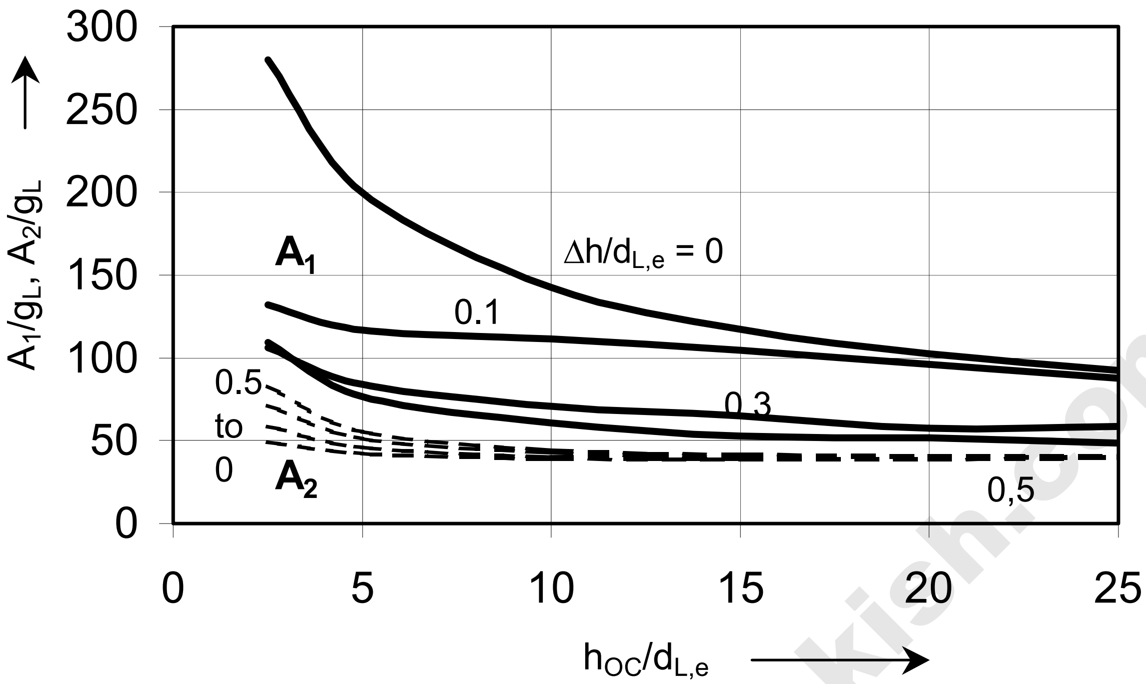
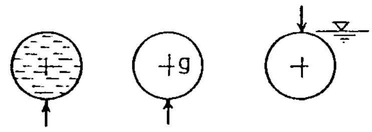
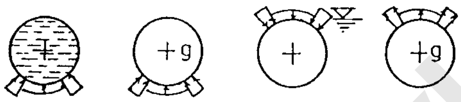
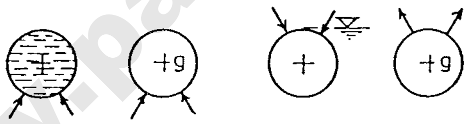


Diagram A1/8: **Support forces of HDPE pipes PN 10 at the old pipe (A_1) and at the edge of the trench (A_2) with draw-in into an old pipe (clearance $\Delta_h/d_{L,e}$)**

Appendix 2
Bending moment and normal force coefficients m and n for loading with annular space filling

	Bending moment coefficient m				Normal force coefficient n			
Bedding case	**Case A** m_W 1)	m_g'	**Case B** m_F 2)	m_g'	**Case A** n_W 1)	n_g	**Case B** n_F 2)	n_g
I (rigid liner)					for sketches see m			
Crown φ = 0°	0.250	0.500	0.750	-1.500	0.750	0.500	-0.750	0.500
Springer 75° 90° 105°	-0.197 -0.285 -0.320	-0.394 -0.571 -0.641	-0.320 -0.285 -0.197	0.641 0.571 0.394	0.303 0.215 0.180	-1.135 -1.571 -1.900	-1.820 -1.785 -1.697	1.900 1.571 1.135
Invert 180°	0.750	1.500	0.250	-0.500	1.250	-0.500	-1.250	-0.500
II/90° (flexible liner)					for sketches see m			
Crown φ = 0°	0.184	0.367	0.182	-0.365	0.613	0.225	-1.389	1.777
Springer 75° 90° 105°	-0.161 -0.214 -0.214	-0.323 -0.429 -0.427	-0.214 -0.214 -0.161	0.427 0.429 0.323	0.268 0.215 0.215	-1.206 -1.571 -1.828	-1.785 -1.785 -1.732	1.828 1.571 1.206
Invert 180°	0.182	0.365	0.184	-0.367	0.611	-1.777	-1.387	-0.225
III/60° (separator, $2\alpha_A = 2 \cdot 30°$					for sketches see m			
Crown φ = 0°	0.176	0.352	0.072	-0.413	0.599.	0.198	-1.506	2.011
Springer 75° 90° 105°	-0.159 -0.208 -0.204	-0.317 -0.416 -0.408	-0.204 -0.208 -0.159	0.408 0.416 0.317	0.264 0.215 0.219	-1.213 -1.571 -1.821	-1.781 -1.785 -1.736	1.821 1.571 1.213
Invert 180°	0.072	0.143	0.176	-0.352	0.494	-2.011	-1.401	-0.198

1) $m_F = -m_W$; $n_F = -n_W$
2) $m_W = -m_F$; $n_W = -n_F$

Case A: sinking of the liner
Case B: floating of liner

Appendix A3/1
Summary of the Verification of the Service Condition

1. Preceding investigations

- results of sewer inspection (comp. Checklist, Appx. A7)
- longitudinal cracks
- imperfections: local prestrain w_v (as a rule 2% of r_L)
  articulated ring prestrain $w_{AR,v}$ (ovalisation)
  gap formation w_s (dependent on lining method)
- other damage (invert washout, gaps in sleeves, sleeve offset, defects etc.)

no longitudinal cracks → Old Pipe Condition I

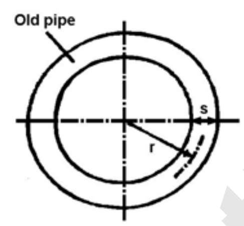
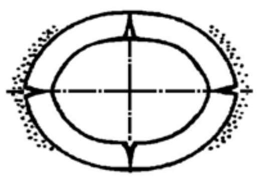
longitudinal cracks → Testing of the old pipe-soil system

2. Additional examinations

Testing of the old pipe-soil system

Long-term observation of vertical pipe deformation $w_{AR,v}$	Soil characteristic values E_2, φ', if nec. c from ram soundings or other examinations and arithmetic verification Eqn. (6.1-3) Appx. 6

Old pipe-soil system: stable → Old Pipe Condition I; $w_{AR,v}$ small → Old Pipe Condition II; $w_{AR,v}$ large → Old Pipe Condition III; long-term no longer stable → Old Pipe Condition III

Step	Old Pipe Condition I	Old Pipe Condition II	Old Pipe Condition III
3. Static system			
4. Effects (loads etc.)	- external water pressure p_e min $h_{W,Inv}$ = 1.5 m or d_e + 0.1 m - internal pressure p_i - temperature change $\Delta\upsilon$ - dead-weight g_L - etc.	- as for Old Pipe Cond. 1	- earth load p_E - traffic loads p_v - if nec. additionally p_e - as for Old Pipe Cond. I
5. Imperfections	- local prestrain w_v - gap formation w_s	- as for Old Pipe Cond. I, additional articulated ring pre-forming $w_{AR,v}$	- articulated ring prestrain $w_{AR,v}$ if p_e is present: additional - local prestrain w_v - gap formation w_s
6. Verification liner: stresses + deformation	Accounting for w_v,w_s: - m/n/δ_v coefficients for p_e in Appx. A4+Eqn. (6.15) $\sigma = N/A+\alpha_k \cdot M/W$ (6.17) - δv i.a.w. Eqn. (6.20) - or second-order theory	- as for Old Pipe Cond. I - additionally: account for $w_{AR,v}$ - coefficients in Appx. A4 - or second-order theory	Accounting for $w_{AR,v}$: - m/n/δ_v coefficients for p_e in Appx. A4+Eqn. (6.15) with p_e: m/n/δ_v coefficient in Appx. A4 + interaction -or second order theory
Stability	- $p_{e,crit} = \kappa_{v,s} \cdot \alpha_{ST} \cdot S_L$ (6.23) with $\kappa_{v,s} \cong \kappa_v \cdot \kappa_s$ (6.25) - or second-order theory	- as for Cond. I, approx: $\kappa_{v,s} \cong \kappa_v \cdot \kappa_{ARv} \cdot \kappa_s$ (6.25) - or second-order theory	- $q_{v,crit} = 167 \cdot \alpha_{qv} \cdot (s_L/r_L)^{2.2}$ (6.38) - with p_e: interaction (6.41) - -or second-order theory
7. If required verification of old pipe	with corrosion wear: stress verification with reduced wall thickness s	- compressive stresses σ_F in the old pipe linkages	- compressive stresses σ_F in the old pipe linkages

Appendix A3/2
Explanatory notes on old pipe conditions

Old pipe condition	**I**	**II**	**III**		
Longitudinal cracks	-	**X**	**X**		**X**
Visual differences between Old Pipe Condition **II-III**	-	Slight ovalisation of cross-section $w_{AR,v}$ < 3-5 %	Greater ovalisation of cross-section $w_{AR,v}$ > 3.5 % (see also Appx. A6)		
Arithmetic differences between Old Pipe Conditions **II-III**	-	$\gamma = \max\left(\frac{q_v}{S_{Bh}}\right) \cdot \frac{S_{Bh}}{q_{v,exist}}$ ≥ 1.5	$\gamma = \max\left(\frac{q_v}{S_{Bh}}\right) \cdot \frac{S_{Bh}}{q_{v,exist}} < 1.5$ (see 6.2, mainly loading from p_E)		
Fundamental loading of the liner	p_e	p_e	$p_E + p_V$		$(p_E + P_V) + p_e$
Loading effects	Liner in **frictional connection**		Liner/old pipe/soil system mainly in **positive locking**		in **frictional connection and positive locking**
Substitute loading with $p_e = 0$ (6.3.1.2)	$h_{W,Inv} = d_e + 0.1$ m, at least $h_{W,Inv} = 1.5$ m		-		-
Safety coefficient γnec (Table 4)	2.0	2.0	1.5		2.0/1.5
Soil parameters	-	-	E_2, φ', K_2		E_2, φ', K_2
Concentration factor of soil above the pipe λ_P (6.3.2.4)	-	-	0.75 (cracks before rehabilitation), 1.5 (cracks after rehabilitation)		
Prestrain for circular cross-sections (6.3.1.1):					
Local prestrain w_v gap formation w_s ovalisation $w_{AR,v}$	≥ 2 % ≥ 0.5 % -	≥ 2 % ≥ 0.5 % ≥ 3 %	0 1) 0 ≥ 3 %		≥ 2 % with p_e 0 ≥ 3 %
Example DN 500	p_e = 60 kN/m²		q_v = 60 kN/m², K_2' = 0.2		
S_{Bh} [N/mm²] =	-	-	2.5	5	
$W_{AR,v}$ =	-	3 %	3 %	3 %	
$m_{pe}, m_q(s_L = 7.5 \text{ mm})$ =	2)	2)	0.025 3)	~ 0.015	←
$m_{pe}, m_q(s_L = 10 \text{ mm})$ =	0.044	0.061	0.050	0.020	←
$m_{pe}, m_q(s_L = 12.5 \text{ mm})$=	0.035	0.050	0.080 4)	0.040	←
n_{pe}, n_q =	ca. -1	ca. -1	ca. -0.2		←

1) As the bending strain as opposed to the normal force strain dominates with positive locking loading, an application of local prestrain is not necessary.
2) With s_L < 10 mm the required buckling safety is undercut.
3) With s_L < 7.5 mm the required buckling safety is undercut.
4) Note: m(max s_L) > m(min s_L) applies, i.e. liners with greater wall thickness receive greater coefficients! For this comp. the water pressure type of loading with reversed behaviour!

The coefficients m_{pe} and m_q of the example show that, for Old Pipe Conditions I and II with external water pressure p_e, stiffer liners are required. On the other hand, considering the danger of stability failure with Old Pipe Condition III and loading q_v, non-rigid liners are an advantage.

Appendix 4
Bending moment and normal force coefficients m_{pe}, n_{pe} and elastic deformation $\delta_{v,el}$ of the liner under external water pressure p_e (Old Pipe Conditions I and II).

Explanatory notes

1. Arithmetical model of the liner-old pipe system

- Rigidly bedded 360° annulus (plain framework) with rigid and movable bearings with prestrain and annular gap
- Exclusion of tensile and tangential forces between liner and old pipe (friction-free contact)
- Truly normal loading through external water pressure p_e (unit weight γ_W = 10 kN/m^3)
- Disregarding of the dead-weight of liner to be on the safe side (γ_L = 0)
- Iteration of the non-linear pressure bending and contact problem
- Load factor 2, following successful iteration the stress resultants are divided by 2
- As a rule the invert of the liner is relevant with small water pressure possibly the crown.

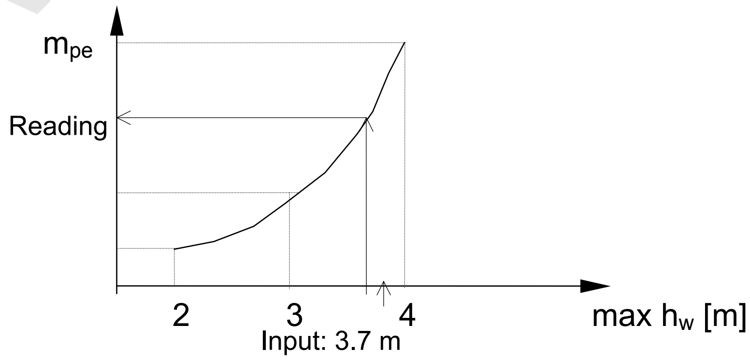
2. Parameters

- Elasticity module **E_L = 1800 N/mm^2**
  For E_L > 1800 N/mm^2 the coefficients lie on the safe side, for 1500 N/mm^2 ≤ E_L ≤ 3000 N/mm^2 the deviation with m_{pe} is less than 10 %.
- Local prestrain **w_v = 2 %** of the liner radius, extension 40 % in the invert.
- Annular gap **w_s = 1 %** of the liner radius (the coefficients for *smaller* annular gaps lie on the safe side).
- Old Pipe Condition II: articulated ring prestrain **$w_{AR,v}$ = 3 %** of the liner radius (ovalisation).

3. Interpolation of coefficients

- For the normal force coefficients npe no interpolation is required as this are approximately constant.
  n_{pe} = -0.8 applies with verification of tensile stresses, n_{pe} = -1.1 applies with verification of compressive stresses.
- Bending moment coefficients m_{pe}
  in the are of approximately parallel curves a linear interpolation is permitted. In the area of heavy bending interpolation is to be non-linear.

Examples for non-linear interpolation of the coefficients m_{pe}



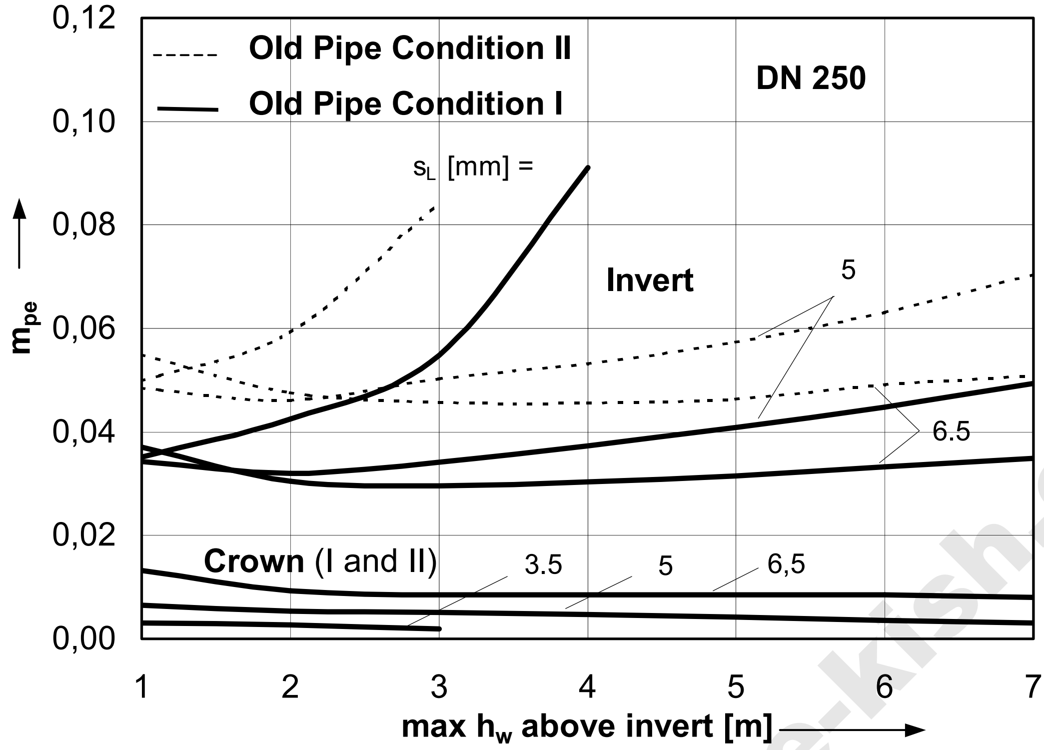


Diagram A4/1: Bending moment coefficients m_{pe} for liners under external water pressure p_e, old pipe DN 200, Old Pipe Conditions I and II; liner E_L = 1800 n/mm²

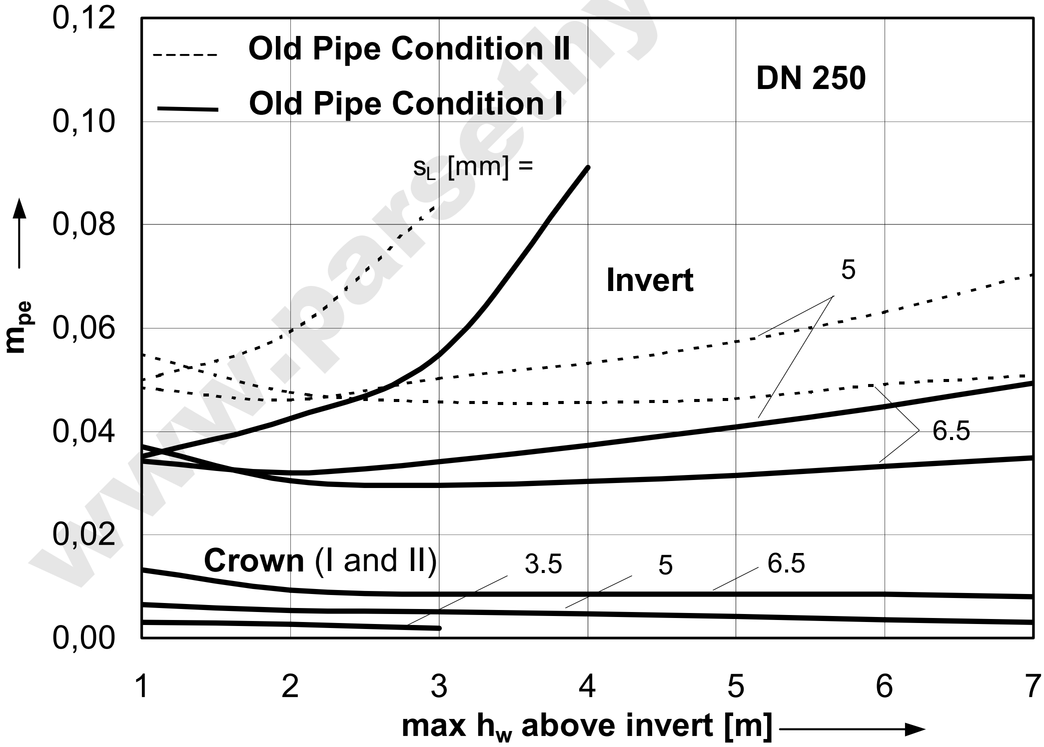


Diagram A4/2: Bending moment coefficients m_{pe} for liners under external water pressure p_e, old pipe DN 250, Old Pipe Conditions I and II; liner E_L = 1800 n/mm²

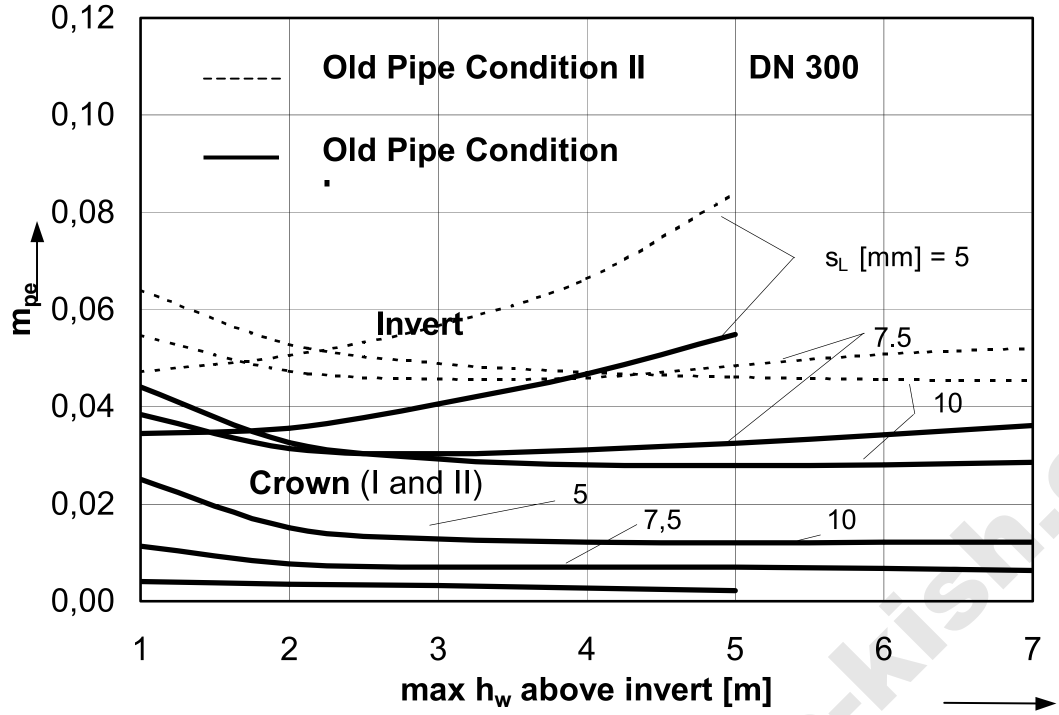


Diagram A4/3: Bending moment coefficients m_{pe} for liners under external water pressure p_e, old pipe DN 300, Old Pipe Conditions I and II; liner E_L = 1800 n/mm^2

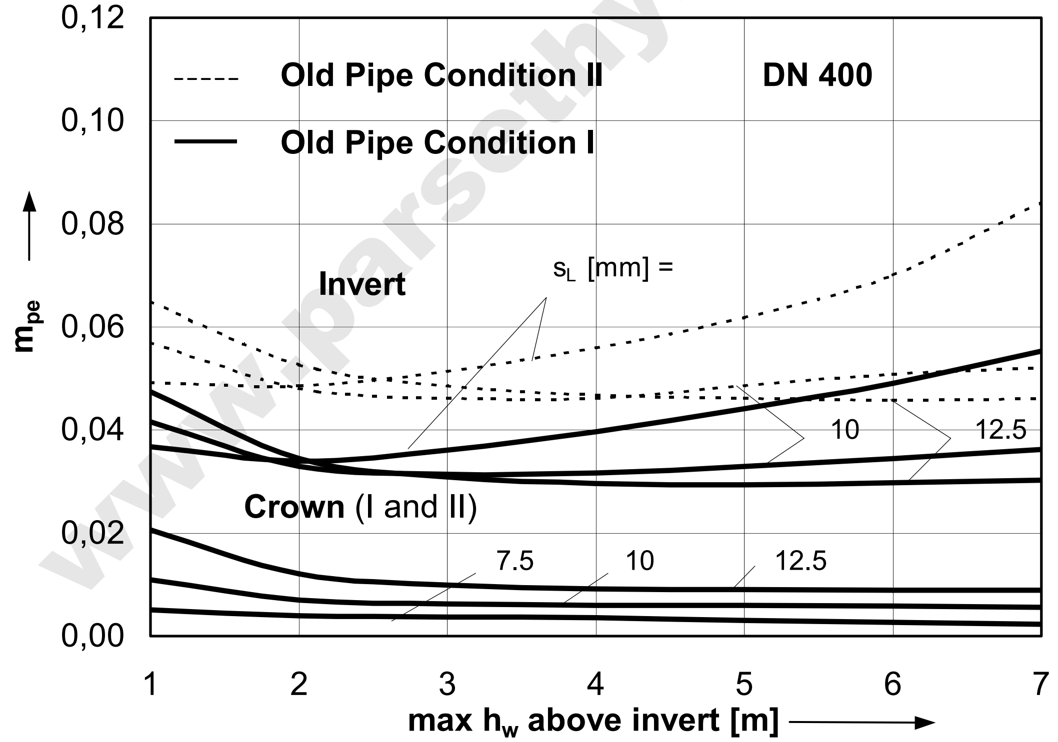


Diagram A4/4: Bending moment coefficients m_{pe} for liners under external water pressure p_e, old pipe DN 400, Old Pipe Conditions I and II; liner E_L = 1800 n/mm^2

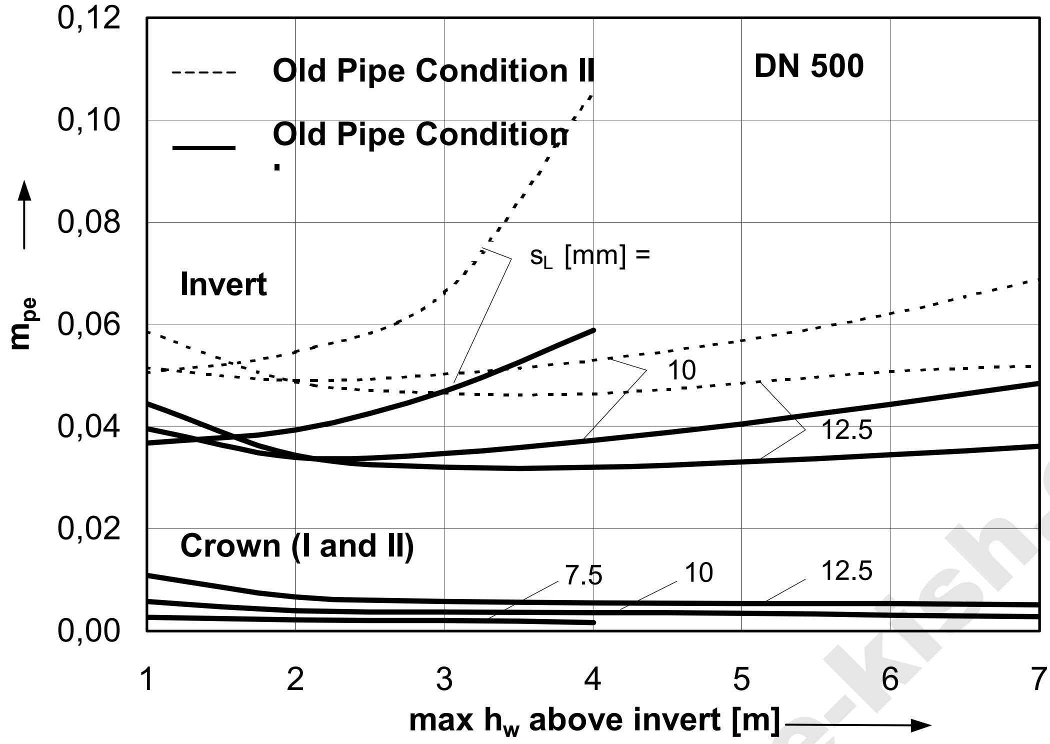


Diagram A4/5: Bending moment coefficients m_{pe} for liners under external water pressure p_e, old pipe DN 500, Old Pipe Conditions I and II; liner E_L = 1800 n/mm^2

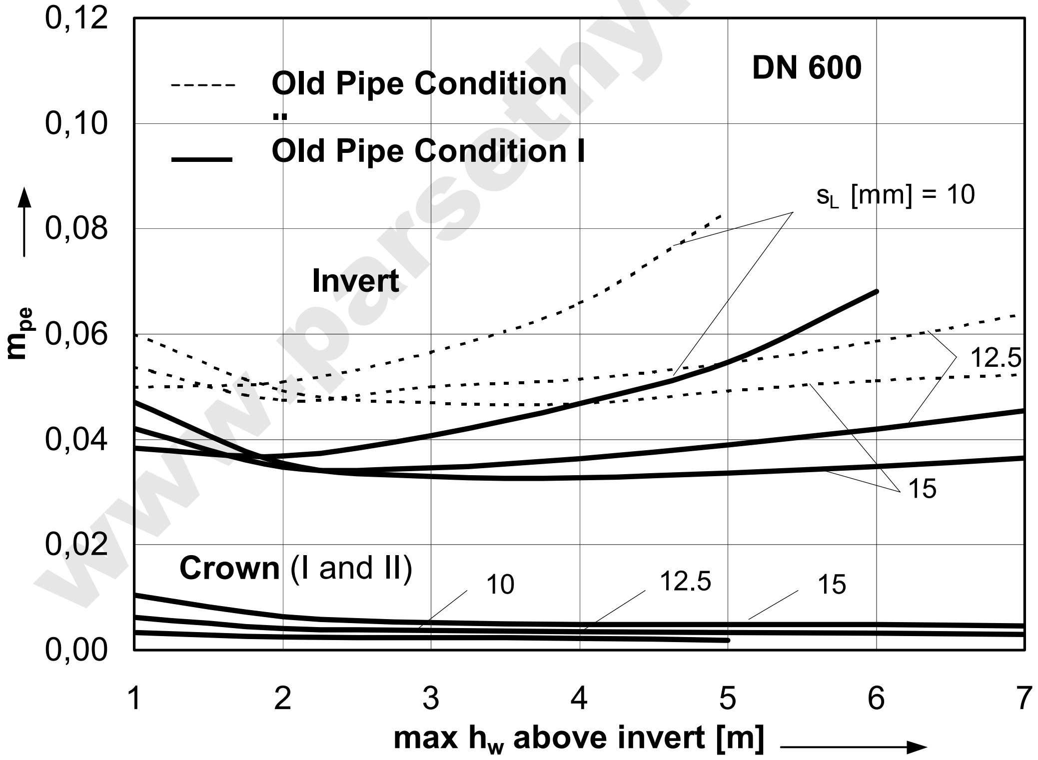


Diagram A4/6: Bending moment coefficients m_{pe} for liners under external water pressure p_e, old pipe DN 600, Old Pipe Conditions I and II; liner E_L = 1800 n/mm^2

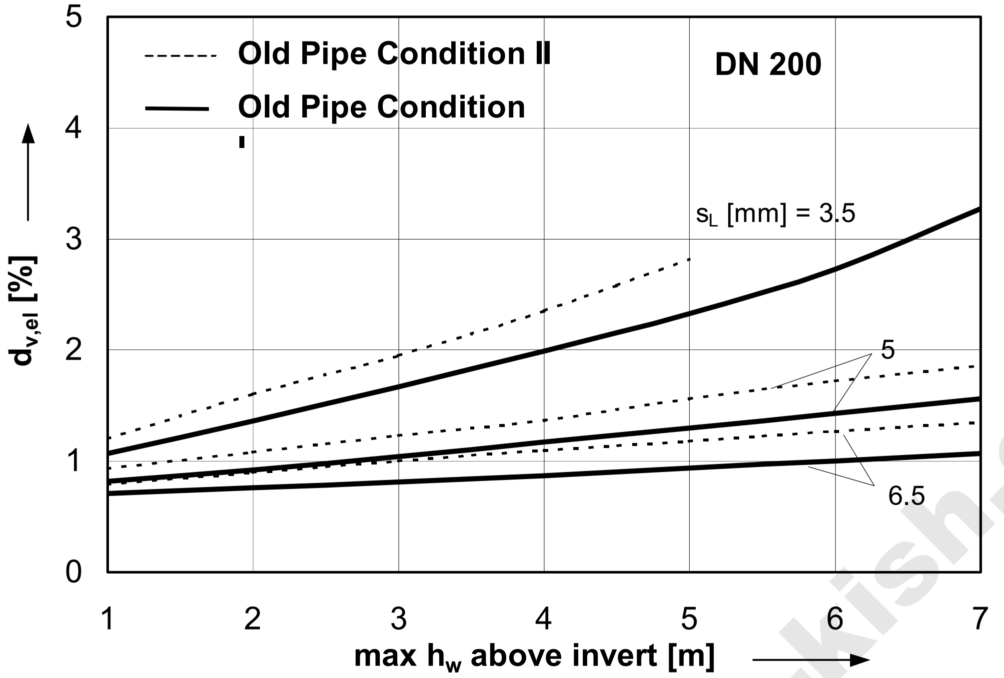


Diagram A4/7: Elastic deformation $\delta_{v,el}$ for liners under external water pressure p_e, old pipe DN 200, Old Pipe Conditions I and II; liner E_L = 1800 n/mm^2

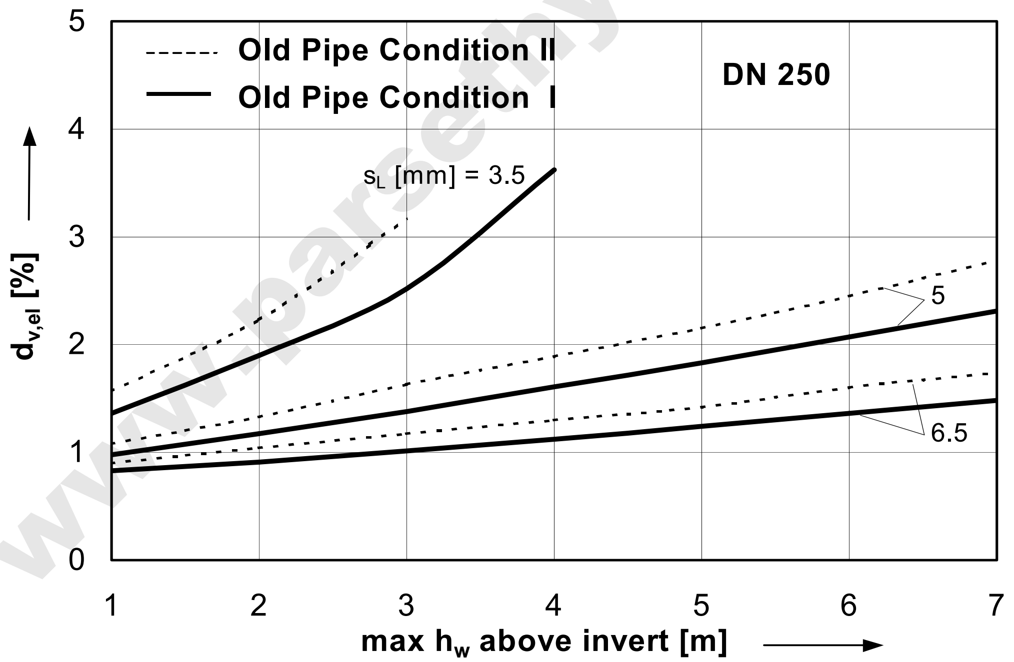


Diagram A4/8: Elastic deformation $\delta_{v,el}$ for liners under external water pressure p_e, old pipe DN 250, Old Pipe Conditions I and II; liner E_L = 1800 n/mm^2

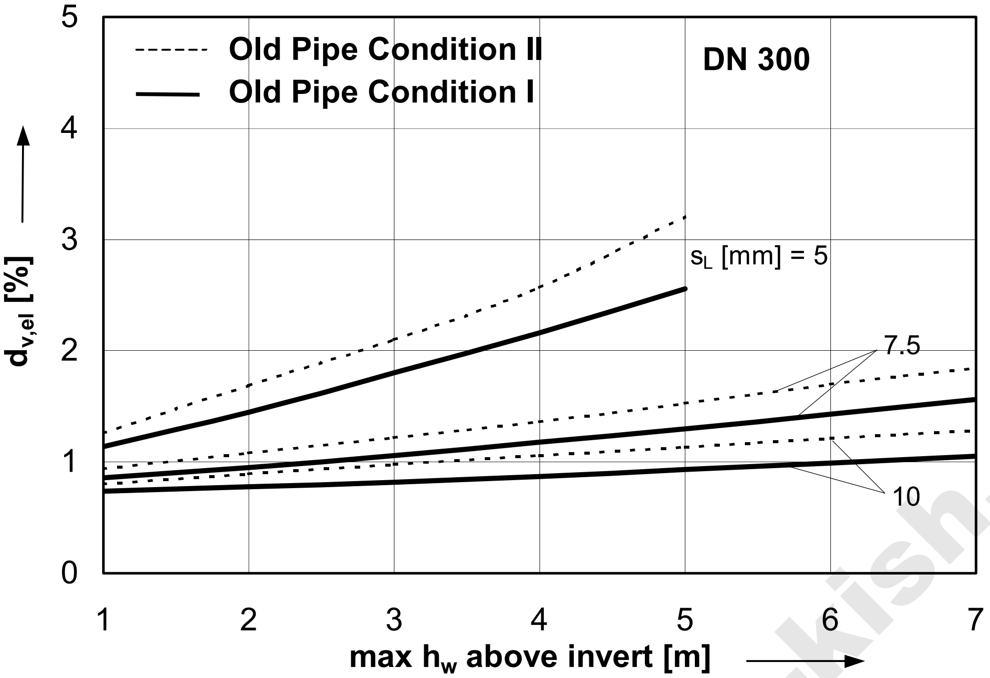


Diagram A4/9: Elastic deformation $\delta_{v,el}$ for liners under extenal water pressure p_e, old pipe DN 300, Old Pipe Conditions I and II; liner E_L = 1800 n/mm^2

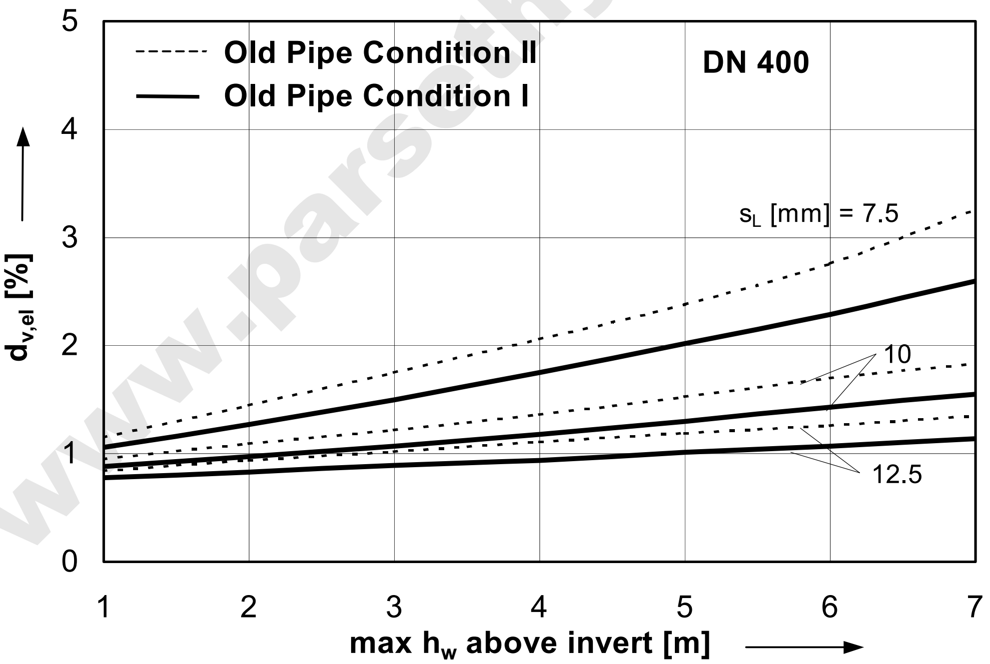


Diagram A4/10: Elastic deformation $\delta_{v,el}$ for liners under external water pressure p_e, old pipe DN 400, Old Pipe Conditions I and II; liner E_L = 1800 n/mm^2

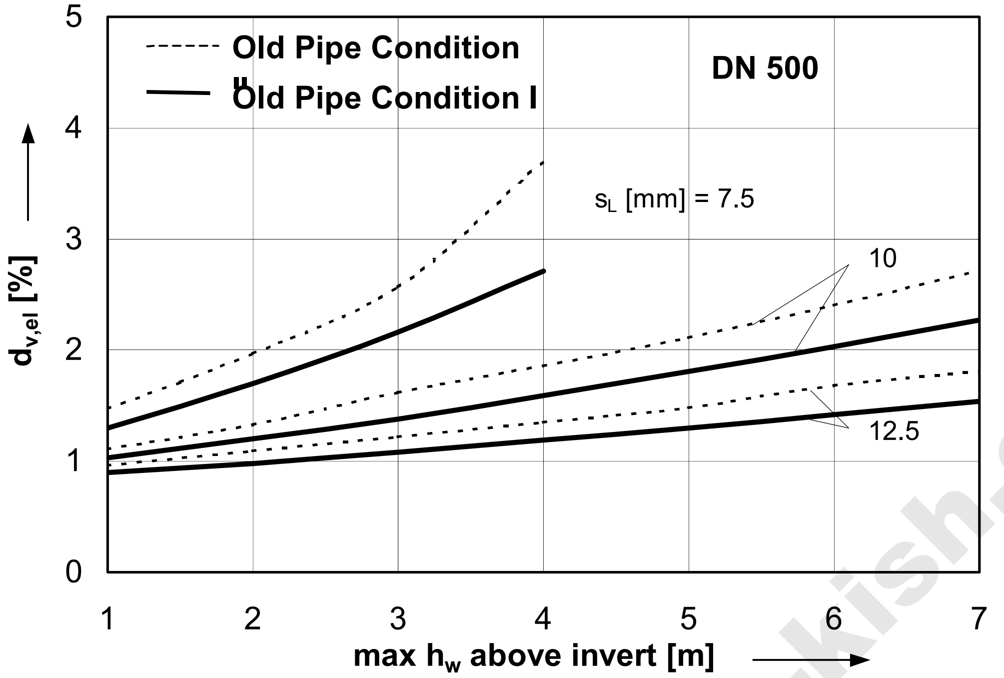


Diagram A4/11: **Elastic deformation $\delta_{v,el}$ for liners under external water pressure p_e, old pipe DN 500, Old Pipe Conditions I and II; liner E_L = 1800 n/mm²**

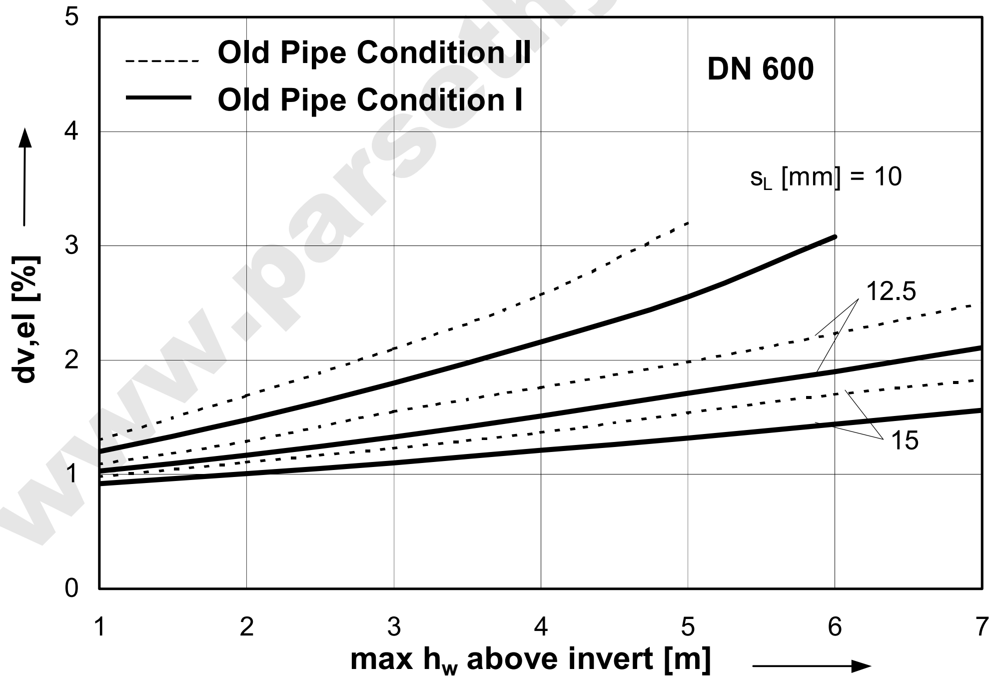


Diagram A4/12: **Elastic deformation $\delta_{v,el}$ for liners under external water pressure p_e, old pipe DN 600, Old Pipe Conditions I and II; liner E_L = 1800 n/mm²**

Appendix 5
Bending moment and normal force coefficients n_q, m_q and elastic deformation $\delta_{v,el}$ of the liner under earth and traffic loads q_v and q_h (Old Pipe Conditions III).

Explanatory notes

1. Arithmetical model of the liner-old pipe system

- Double symmetric loading through earth and traffic loads
- External water pressure: treatment as for Condition II, comp. Appx. A4
- 90° FEM model, even deformation condition
- Exclusion of tensile and tangential forces between liner and old pipe (friction-free contact
- Constant directionally true earth and traffic loads q_v and q_h
- Iteration of the non-linear compressive bending and contact problem
- Load factor 2, following successful iteration the stress resultants are divided by 2
- Crown of liner or the invert relevant (coefficients are the same size)

2. Parameters

- Elasticity modulus of the liner **E_L = 2000 N/mm²**
  For E_L < 2000 N/mm² the coefficients m_q lie on the safe side, however produce larger elastic deformation $\delta_{v,el}$.
  With 2000 N/mm² < EL ≤ ca. 2300 N/mm² m_q is exceeded by a maximum of 10 %.
- Arithmetical earth pressure coefficient **$q_v/q_h = K_2' = 0.2$**
  With K_2' > 0.2 small stresses result, for K_2' < 0.2 the following diagrams are invalid.
- Link eccentricities crown **$e_J = +0.25 \cdot s$** (outwards), springers $e_J = -0.25 \cdot s$ (inwards), larger eccentricities lead to smaller stresses.
- The thicknesses of the old pipe walls s are selected unfavourably as minimum value:

DN	200	250	300	400	500	600
s	**20 mm**	**23 mm**	**25 mm**	**30 mm**	**40.5 mm**	**43.5 mm**

  For s_{exist} > s the coefficients m_q lie on the safe side; for $0.9 \cdot s < s_{exist}$ the coefficients m_q apply approximately; for $s_{exist} < 0.9 \cdot s$ the following diagrams are invalid.
- Local prestrain of the liner with earth and traffic loads has only a slight influence and is therefore neglected. Therefore **$w_v = 0$** applies.
- Articulated ring prestrain **$w_{AR,v}$ = 0.3 % and 6 %** of the liner radius (ovalisation
- Annular gap **$w_s = 0$**
  Larger annular gaps have lead to smaller stresses with loadings q_v and q_h and are therefore are to be neglected (as opposed to the load case external water pressure p_e, comp. Appx. A4).

3. Interpolation of coefficients

- Normal force coefficient n_q:
  intermediate values may be interpolated linearly
- Bending moment coefficients m_q:
  non-linear interpolation (see example)

Example for the non-linear interpolation of m-coefficients:

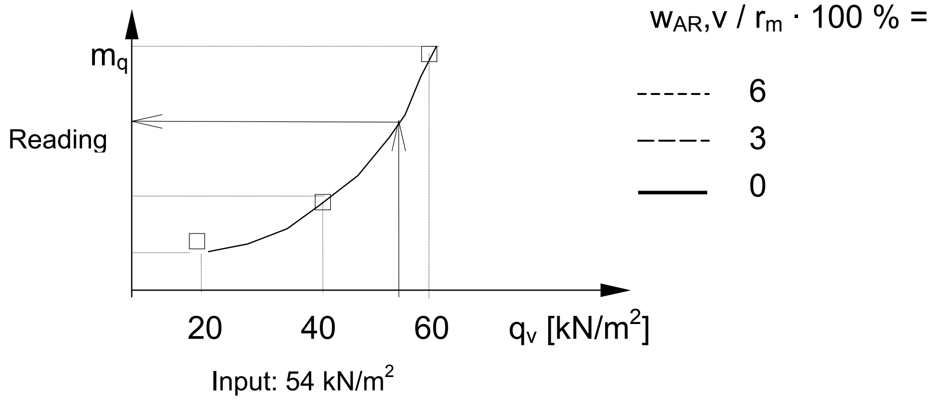


Diagram A5.1/1: **Bending moment coefficients m_q for liners under earth and traffic loads p_v, old pipe DN 200, Old Pipe Condition III; liner E_L = 2000 n/mm²; soil S_{Bh} = 2.5 N/mm²**

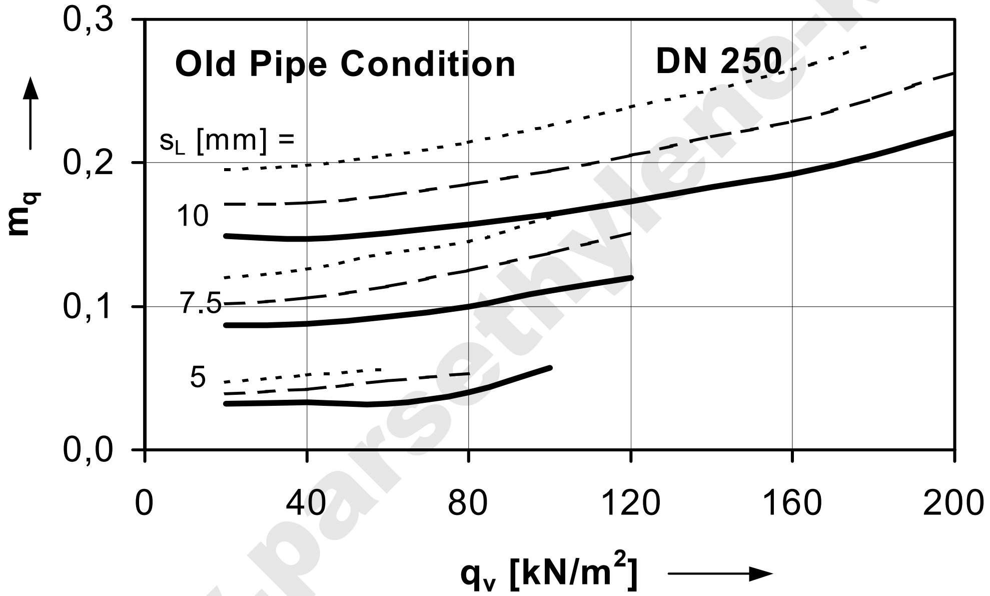


Diagram A5.1/2: **Bending moment coefficients m_q for liners under earth and traffic loads p_v, old pipe DN 250, Old Pipe Condition III; liner E_L = 2000 n/mm²; soil S_{Bh} = 2.5 N/mm²**

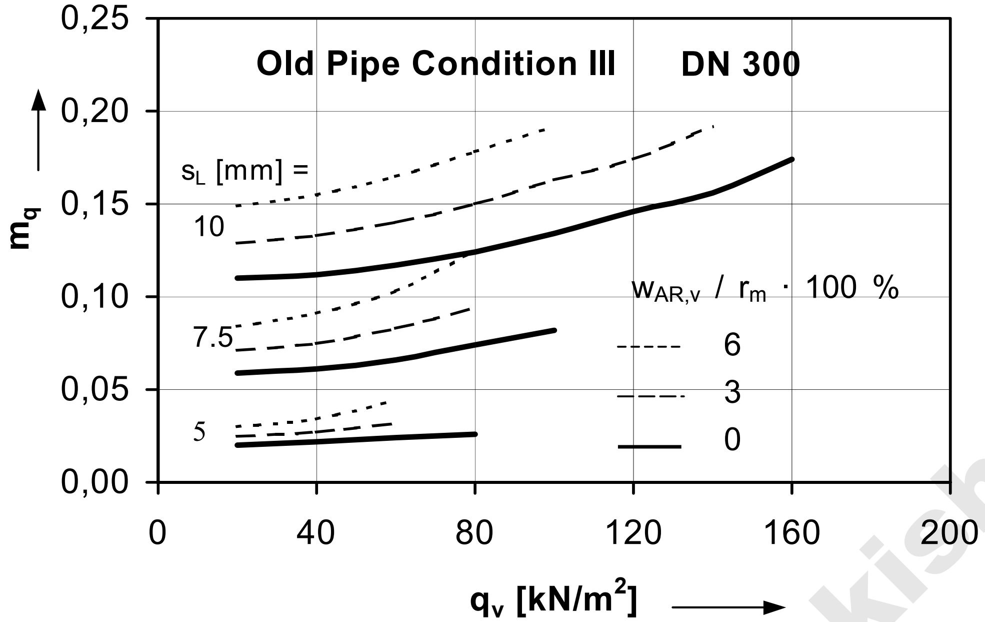


Diagram A5.1/3: **Bending moment coefficients m_q for liners under earth and traffic loads p_v, old pipe DN 300, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 2.5 N/mm^2**

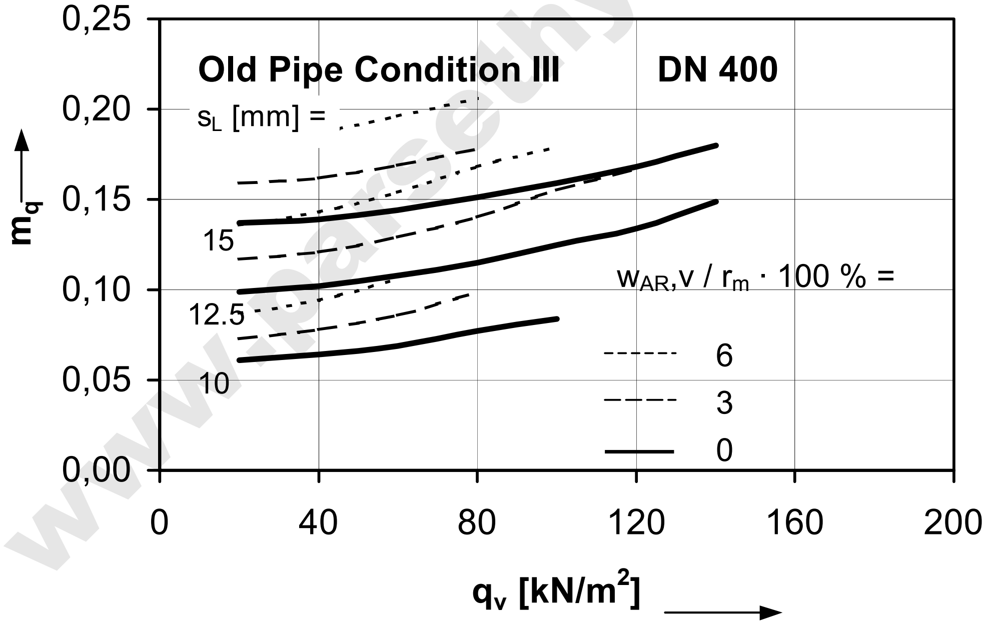


Diagram A5.1/4: **Bending moment coefficients m_q for liners under earth and traffic loads p_v, old pipe DN 400, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 2.5 N/mm^2**

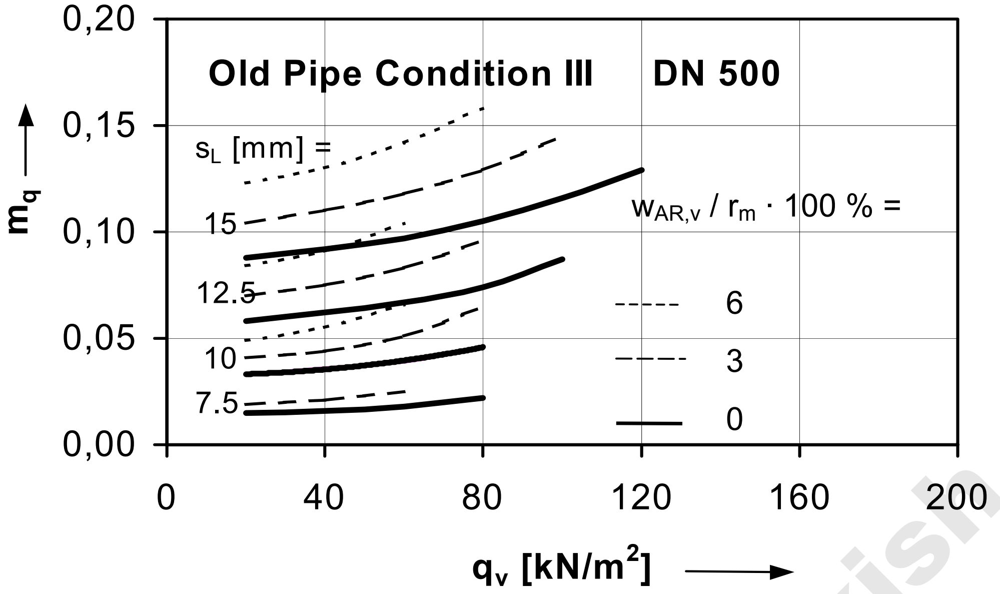


Diagram A5.1/5: **Bending moment coefficients m_q for liners under earth and traffic loads p_v, old pipe DN 500, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 2.5 N/mm^2**

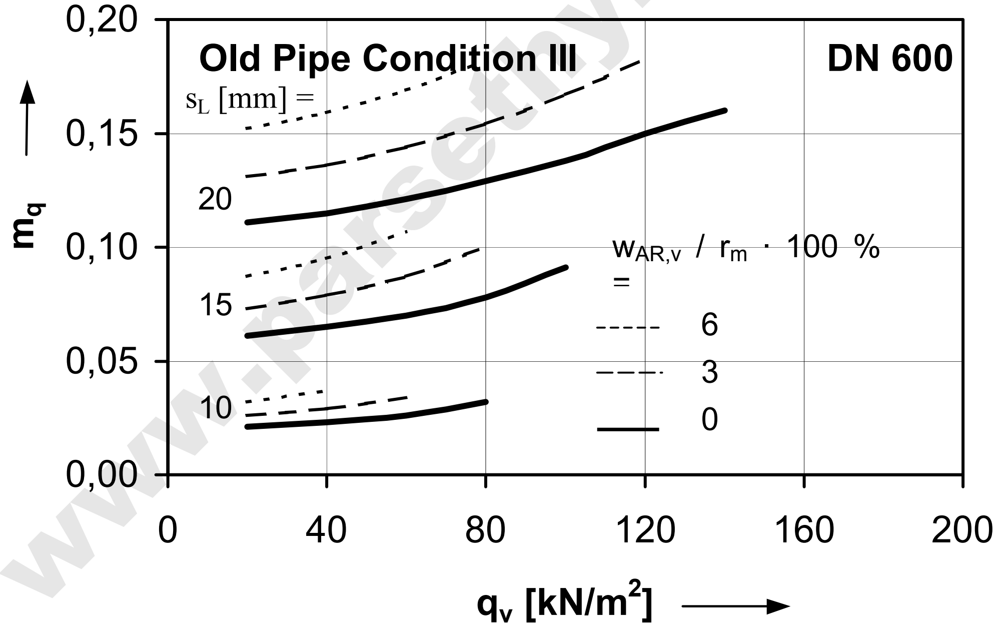


Diagram A5.1/6: **Bending moment coefficients m_q for liners under earth and traffic loads p_v, old pipe DN 600, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 2.5 N/mm^2**

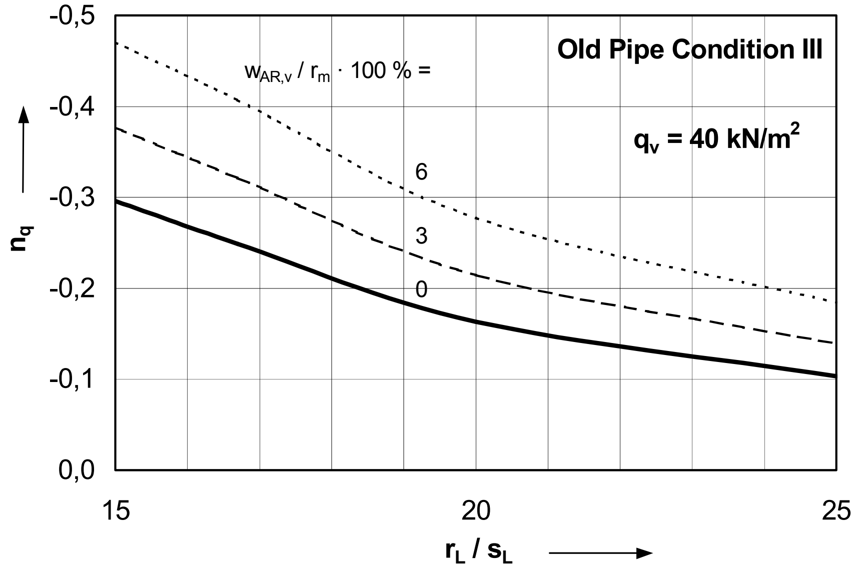


Diagram A5.1/7: **Normal force coefficients n_q for liners under earth and traffic loads p_v, old pipe DN 200 to DN 600, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 2.5 N/mm^2, loading q_v = 40 kN/m^2**

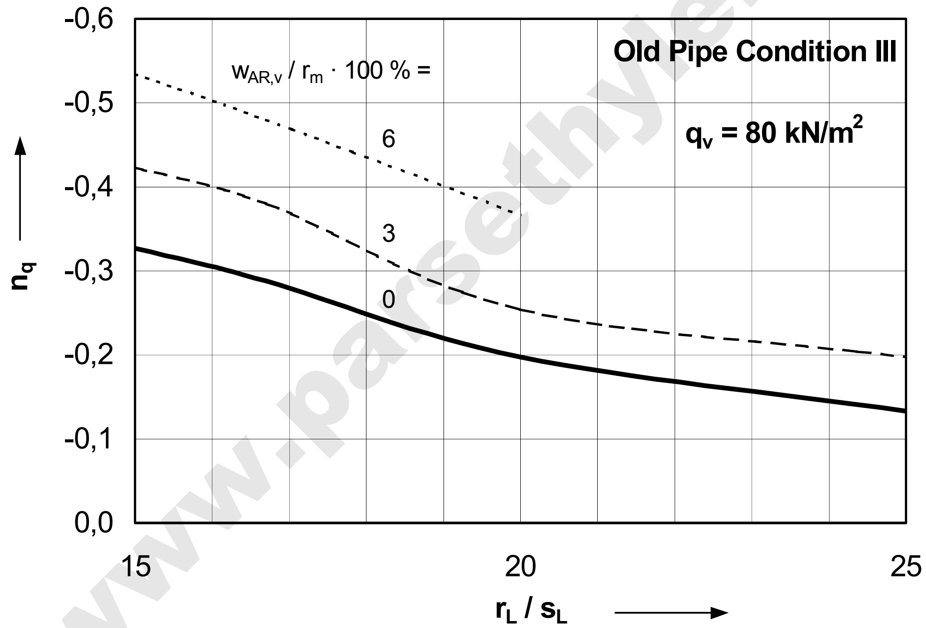


Diagram A5.1/8: **Normal force coefficients n_q for liners under earth and traffic loads p_v, old pipe DN 200 to DN 600, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 2.5 N/mm^2, loading q_v = 80 kN/m^2**

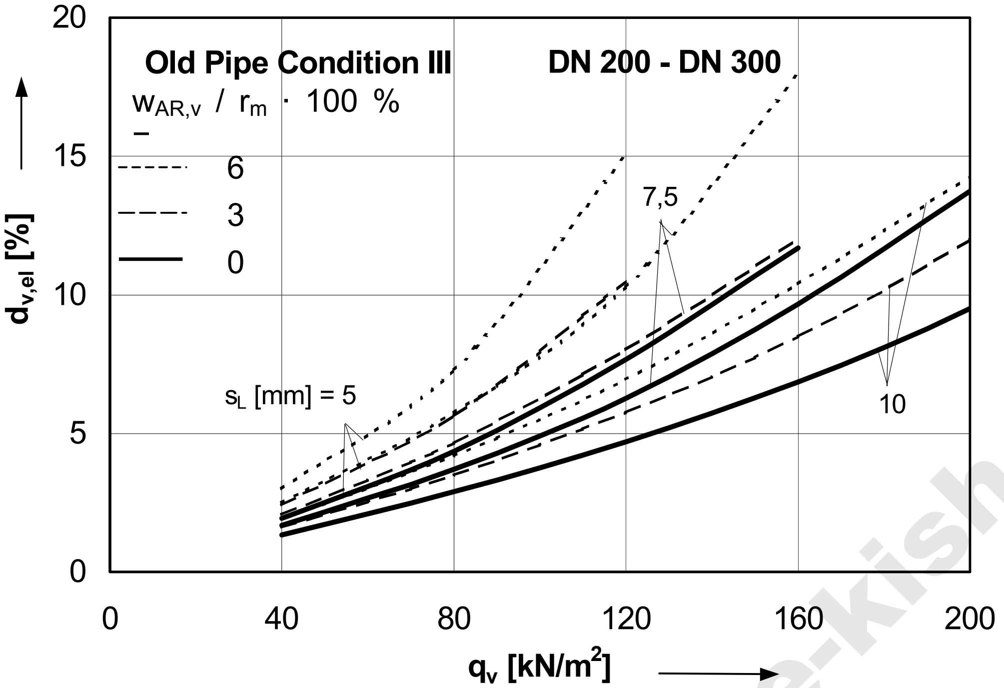


Diagram A5.1/9: **Elastic defomation $\delta_{v,el}$ for liners under earth and traffic loads p_v, old pipe DN 200 to DN 300, Old Pipe Condition III; liner E_L = 2000 n/mm²; soil S_{Bh} = 2.5 N/mm²**

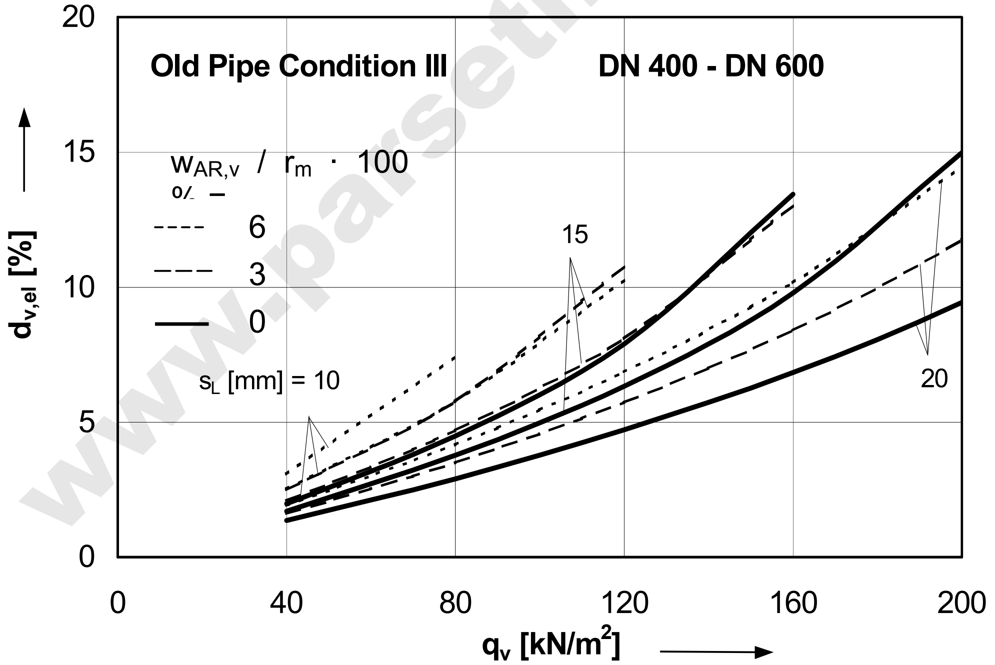


Diagram A5.1/10: **Elastic defomation $\delta_{v,el}$ for liners under earth and traffic loads p_v, old pipe DN 400 to DN 600, Old Pipe Condition III; liner E_L = 2000 n/mm²; soil S_{Bh} = 2.5 N/mm²**

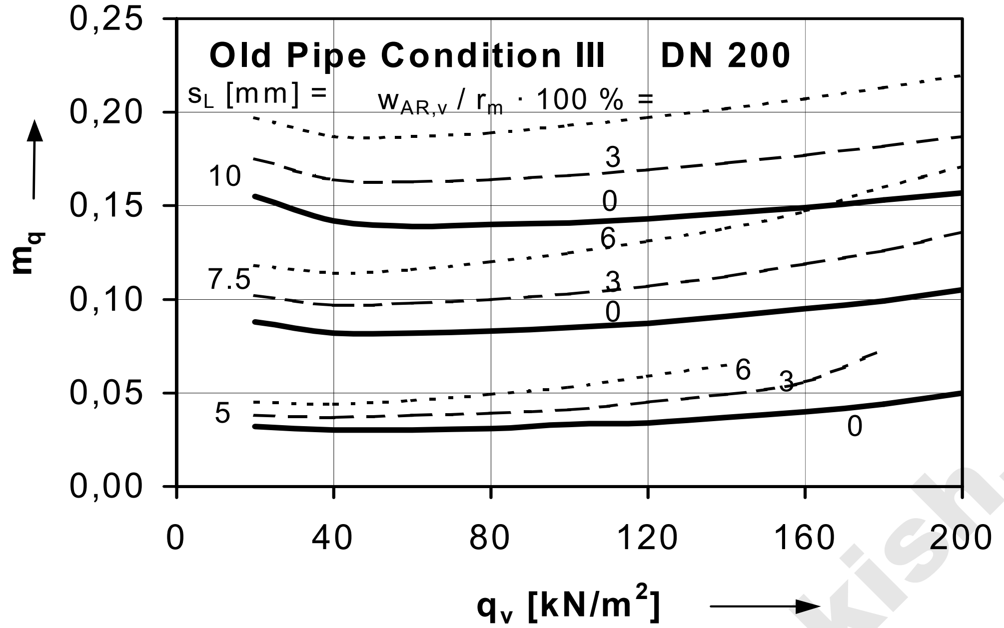


Diagram A5.2/1: **Bending moment coefficients m_q for liners under earth and traffic loads q_v, old pipe DN 200, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 5 N/mm^2**

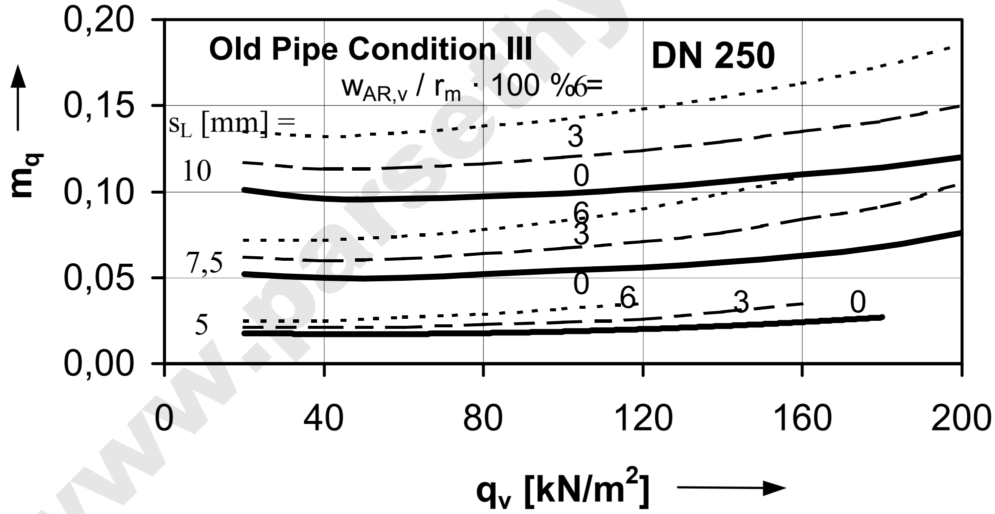


Diagram A5.2/2: **Bending moment coefficients m_q for liners under earth and traffic loads q_v, old pipe DN 250, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 5 N/mm^2**

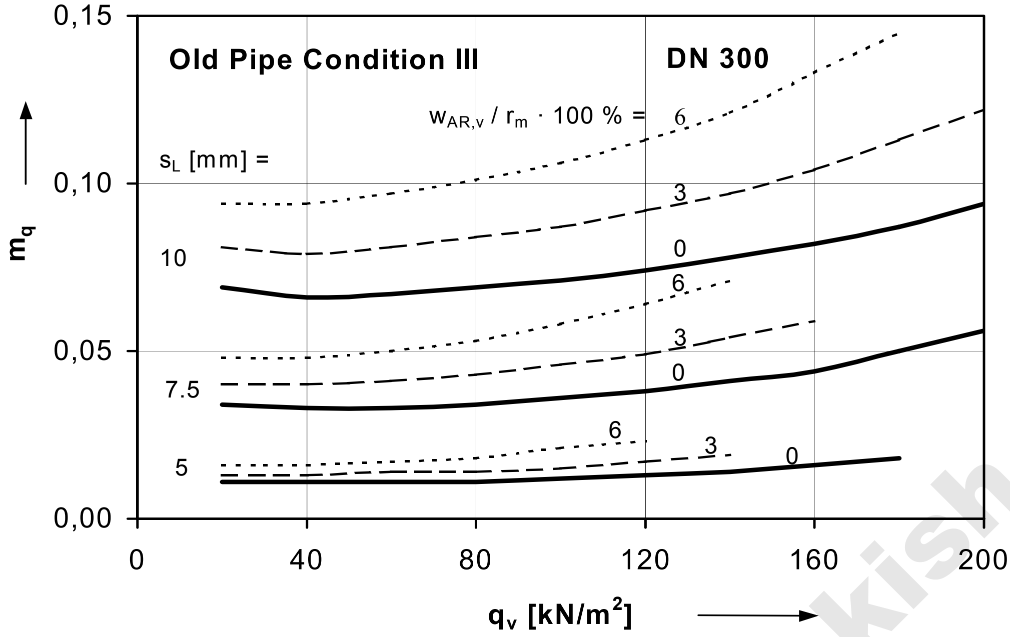


Diagram A5.2/3: **Bending moment coefficients m_q for liners under earth and traffic loads q_v, old pipe DN 300, Old Pipe Condition III; liner E_L = 2000 n/mm²; soil S_{Bh} = 5 N/mm²**

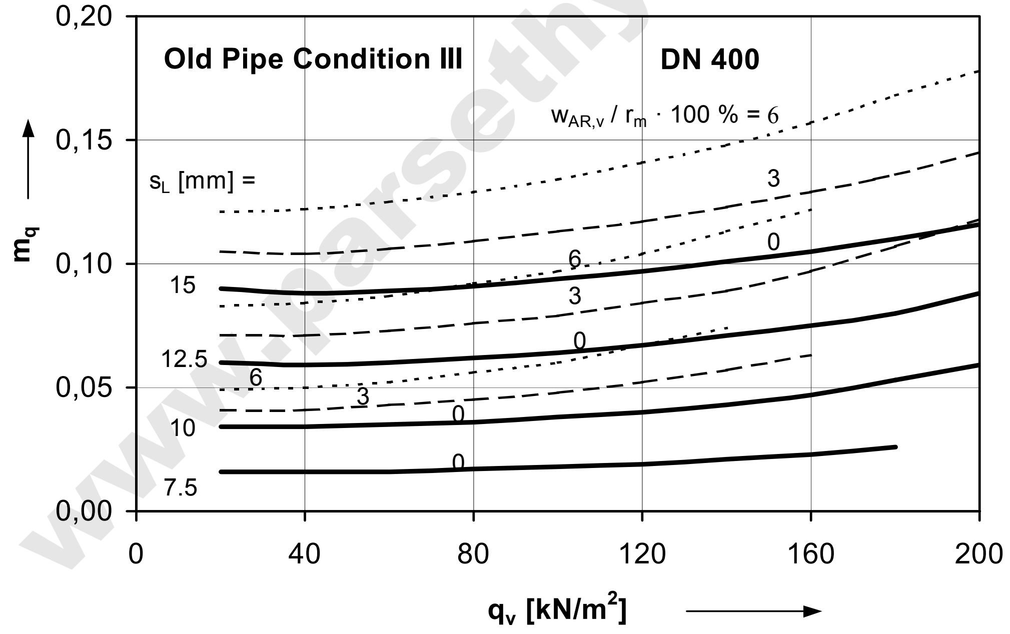


Diagram A5.2/4: **Bending moment coefficients m_q for liners under earth and traffic loads q_v, old pipe DN 400, Old Pipe Condition III; liner E_L = 2000 n/mm²; soil S_{Bh} = 5 N/mm²**

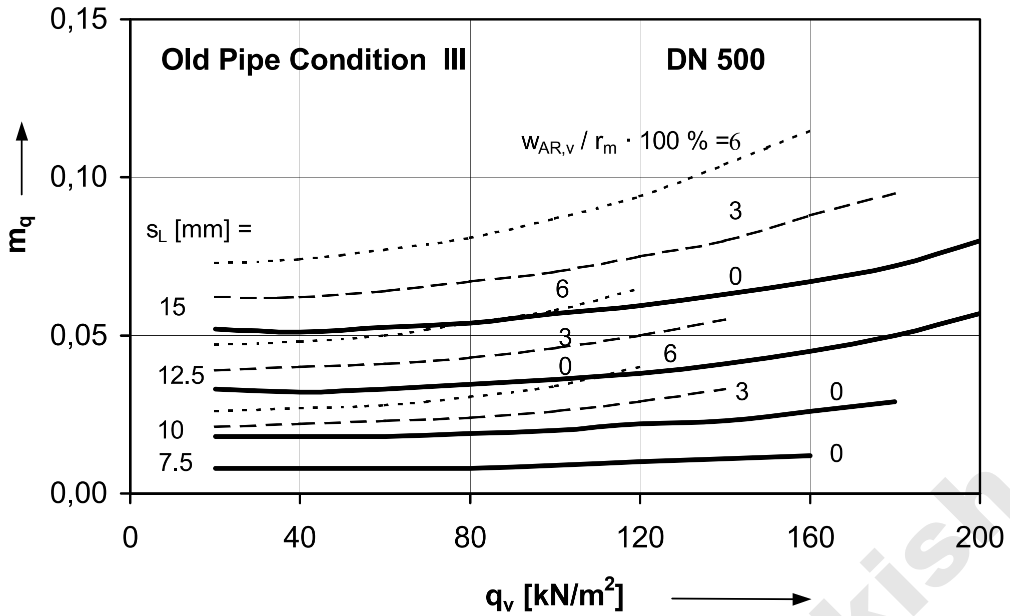


Diagram A5.2/5: **Bending moment coefficients m_q for liners under earth and traffic loads q_v, old pipe DN 500, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 5 N/mm^2**

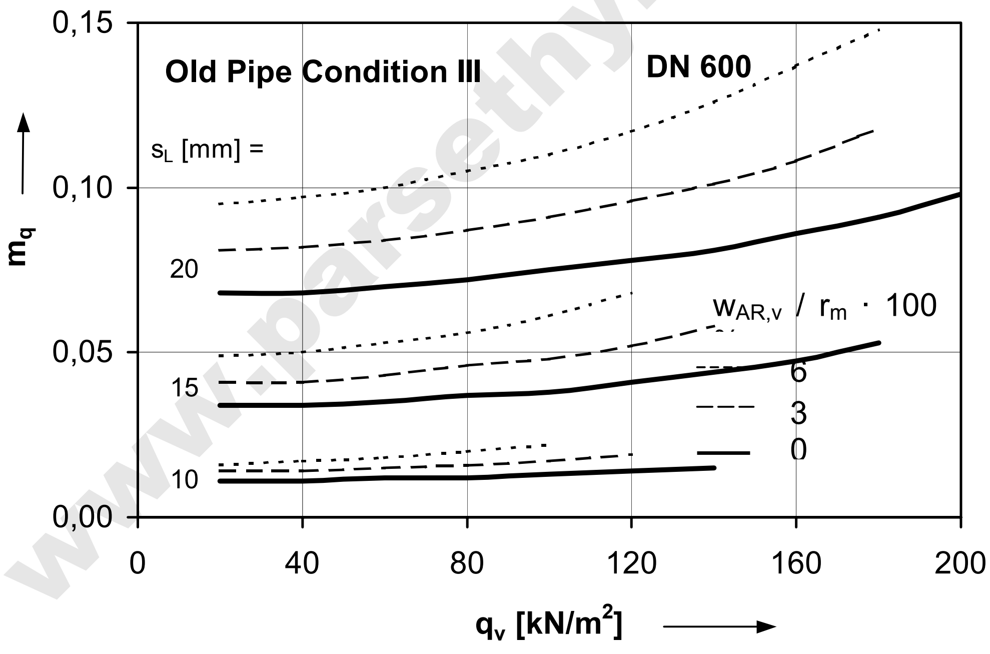


Diagram A5.2/6: **Bending moment coefficients m_q for liners under earth and traffic loads q_v, old pipe DN 600, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 5 N/mm^2**

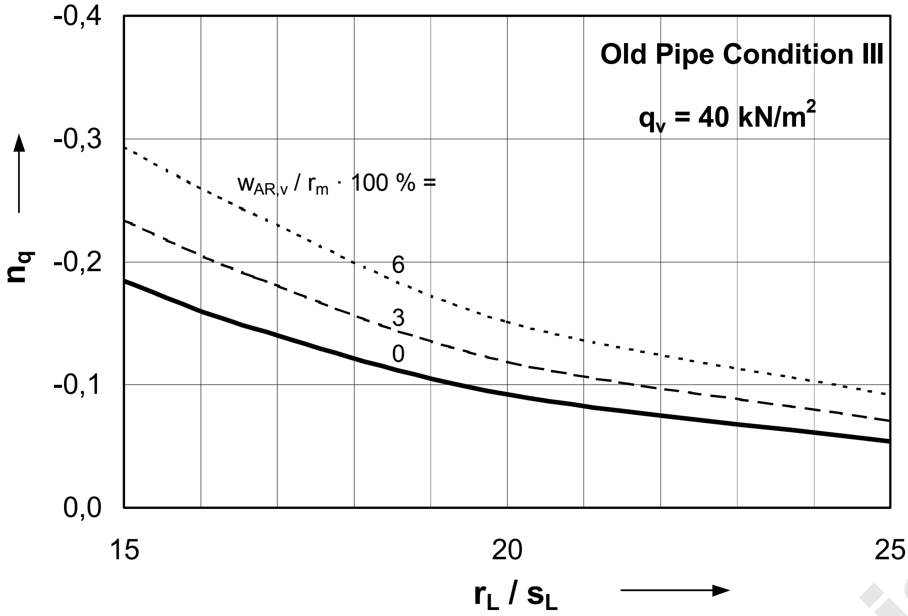


Diagram A5.2/7: **Normal force coefficients n_q for liners under earth and traffic loads q_v, old pipe DN 200 to DN 600, Old Pipe Condition III; liner E_L = 2000 n/mm²; soil S_{Bh} = 40 kN/m²**

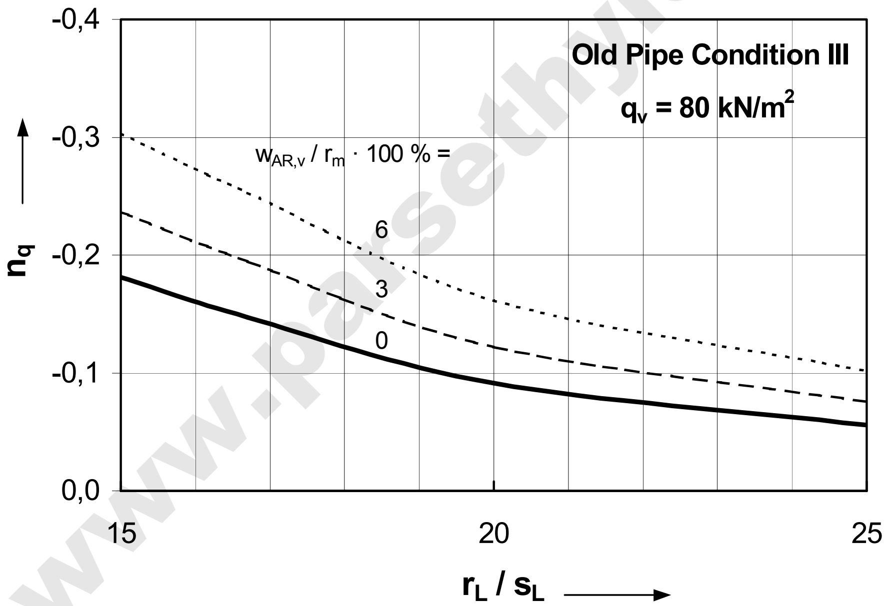


Diagram A5.2/8: **Normal force coefficients n_q for liners under earth and traffic loads q_v, old pipe DN 200 to DN 600, Old Pipe Condition III; liner E_L = 2000 n/mm²; soil S_{Bh} = 80 kN/m²**

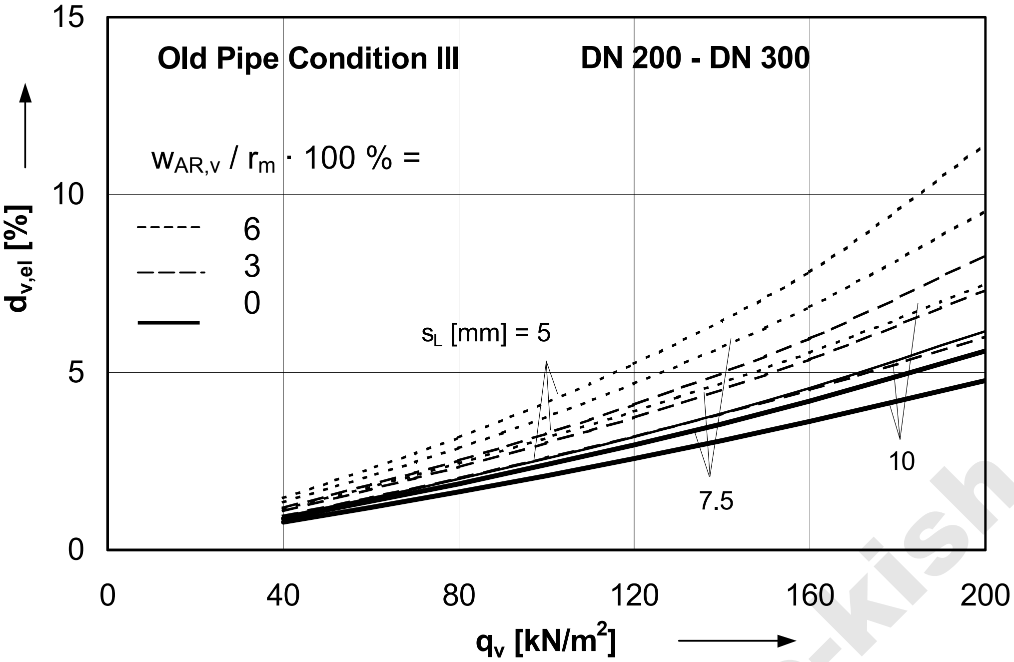


Diagram A5.2/9: **Elastic deformation $\delta_{v,el}$ for liners under earth and traffic loads q_v, old pipe DN 200 to DN 300, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 5 N/mm^2**

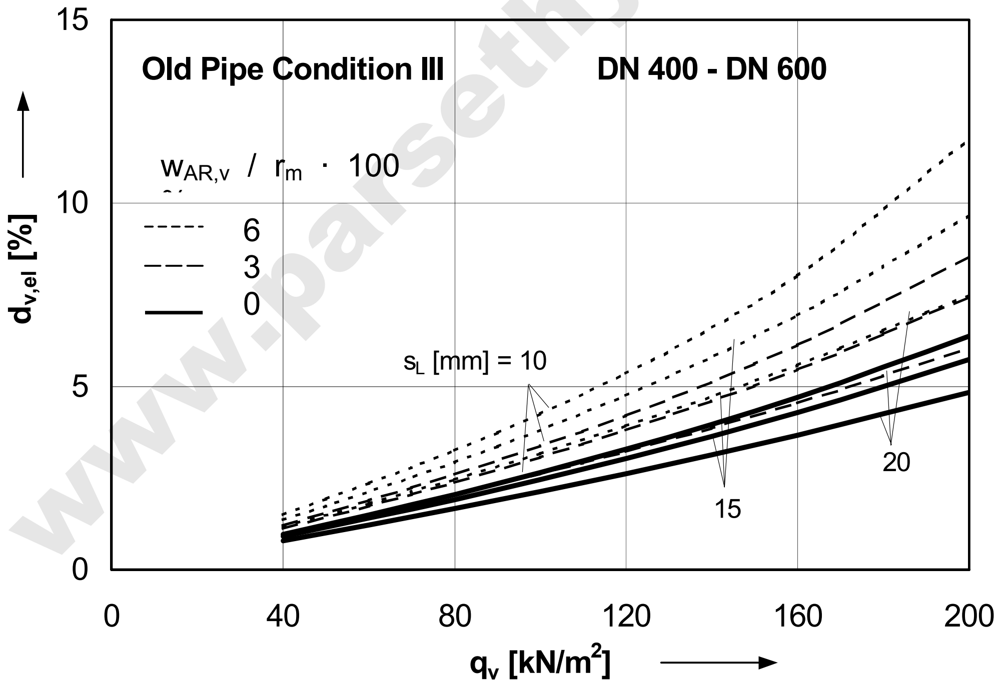


Diagram A5.2/10: **Elastic deformation $\delta_{v,el}$ for liners under earth and traffic loads q_v, old pipe DN 400 to DN 600, Old Pipe Condition III; liner E_L = 2000 n/mm^2; soil S_{Bh} = 5 N/mm^2**

Appendix 6
Load-displacement curves for the determination of q_v, $q_{v,crit}$ and $p_{e,crit}$ of the old pipe-soil system

Explanatory notes

With the aid of the load-displacement curves of the four-link system it is possible,

- to read the snap-through loads of the system related to the horizontal bedding stiffness S_{Bh} and
- with specified loading p and deformation δ_v of an old pipe in Condition III to estimate the horizontal bedding stiffness S_{Bh} of the old pipe-soil system.

The diagrams are given for the normal case of links with an eccentricity of $e_J = s/4$ (unbroken line) and the special case central link $e_J = 0$ (dashed line. The less favourable case of central links is to be assumed with a poor condition of the old pipe (corrosion, spalling etc.).

In all cases the radius/wall thickness ratio is assumed to be $s/r_i = 0.15$. The curves apply as approximation also for divergent conditions.

The particularly small results of max (p_V/S_{Bh}) with traffic loads are justified in that, in accordance with ATV-DVWK-A 127E no side pressure is applied from p_V. In justified exceptional cases a side pressure can be assumed (e.g. smaller nominal widths and greater covering) - in this case the traffic load p_V can be added to the earth load as an approximation.

Intermediate values with small divergence from the specified exceptions may be interpolated.

Assumptions:

All curves in the elastic soil condition are dependent on S_{Bh}. with plastic soil conditions (steeply falling branch of the curve) the assumption of $S_{Bh} = 5$ N/mm^2 is met.

- **Earth pressure q_v only (without traffic loads)**
  Diagram A6/1: Soil Group 2 with $K_2 = 0.3$ and $\varphi' = 30°$
  Diagram A6/2: Soil Group 3 with $K_2 = 0.2$ and $\varphi' = 25°$

- **Traffic loads p_v**
  (simultaneously effective: $p_E = 20$ kN/m^2)
  Diagram A6/3: Soil Group 1 with $K_2 = 0.4$ and $\varphi' = 35°$
  Diagram A6/4: Soil Group 2 with $K_2 = 0.3$ and φ' 30°

- **External Water pressure p_e**
  (simultaneously effective: $p_E = 20$ kN/m^2)
  Diagram A6/5: Soil Group 1 with $K_2 = 0.4$ and $\varphi' = 35°$
  Diagram A6/6: Soil Group 2 with $K_2 = 0.3$ and $\varphi' = 30°$

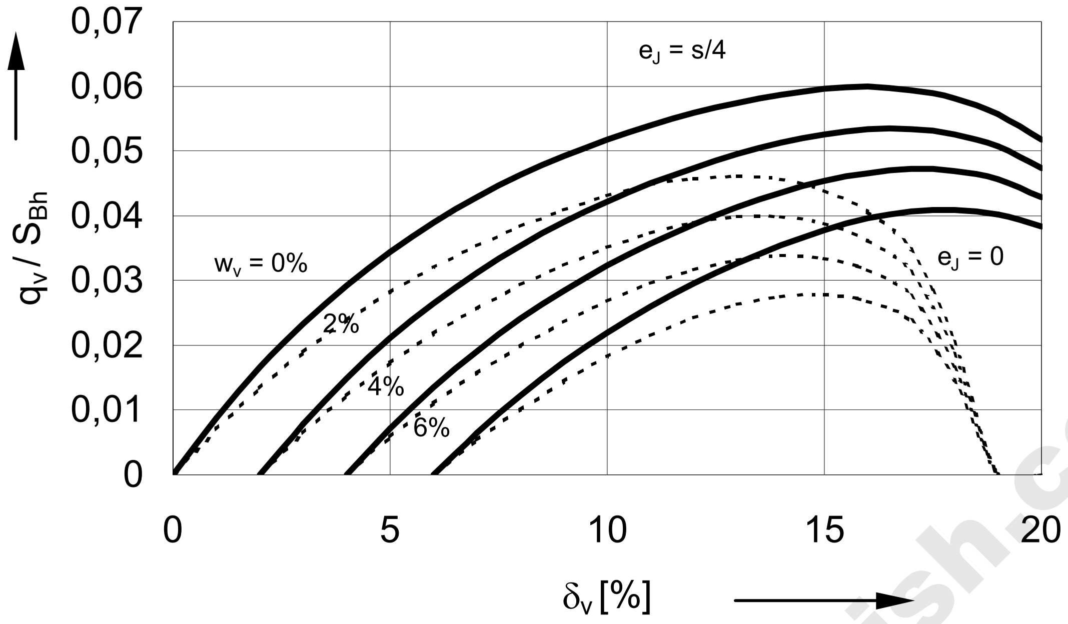


Diagram A6/1: **Load displacement curves of the four-link ring for earth loads q_v $p_v = 0$ (low lying pipes); Soil Group 2; independent of S_{Bh}**

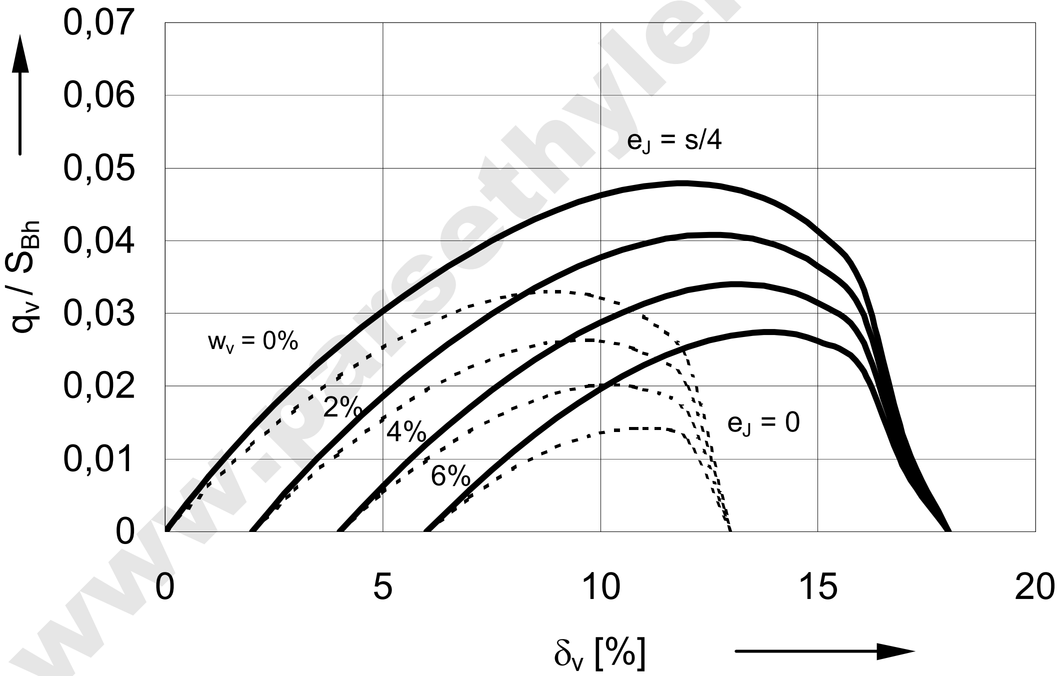


Diagram A6/2: **Load displacement curves of the four-link ring for earth loads q_v $p_v = 0$ (low lying pipes); Soil Group 3; in the plastic range valid for S_{Bh} = 5 N/mm2 only**

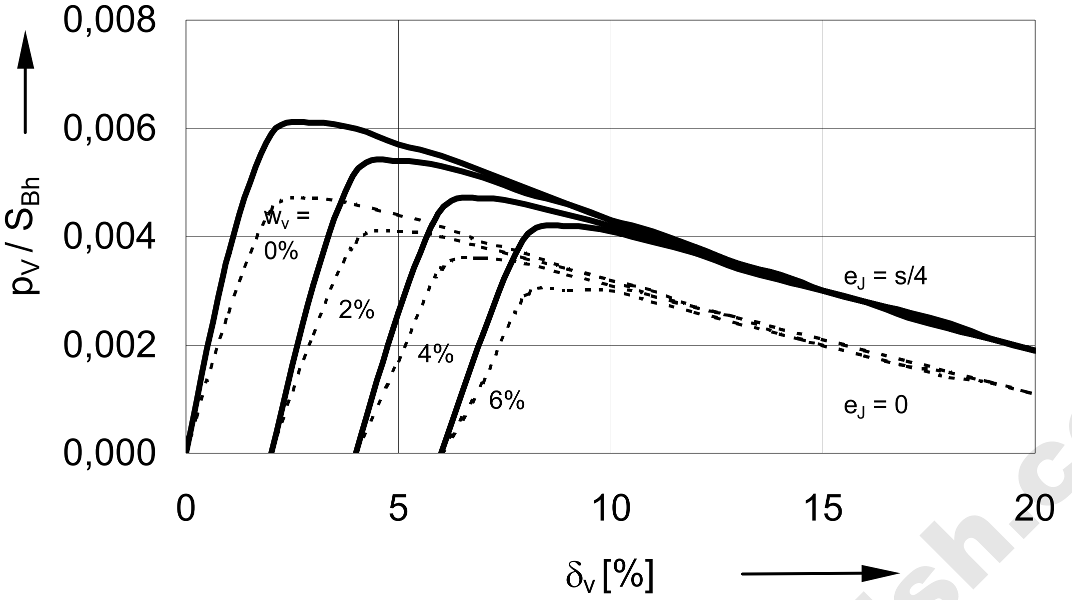


Diagram A6/3: **Load displacement curves of the four-link ring for earth loads q_v p_E = 20 kN/m², Soil Group 1; valid for S_{Bh} = 5 N/mm²**

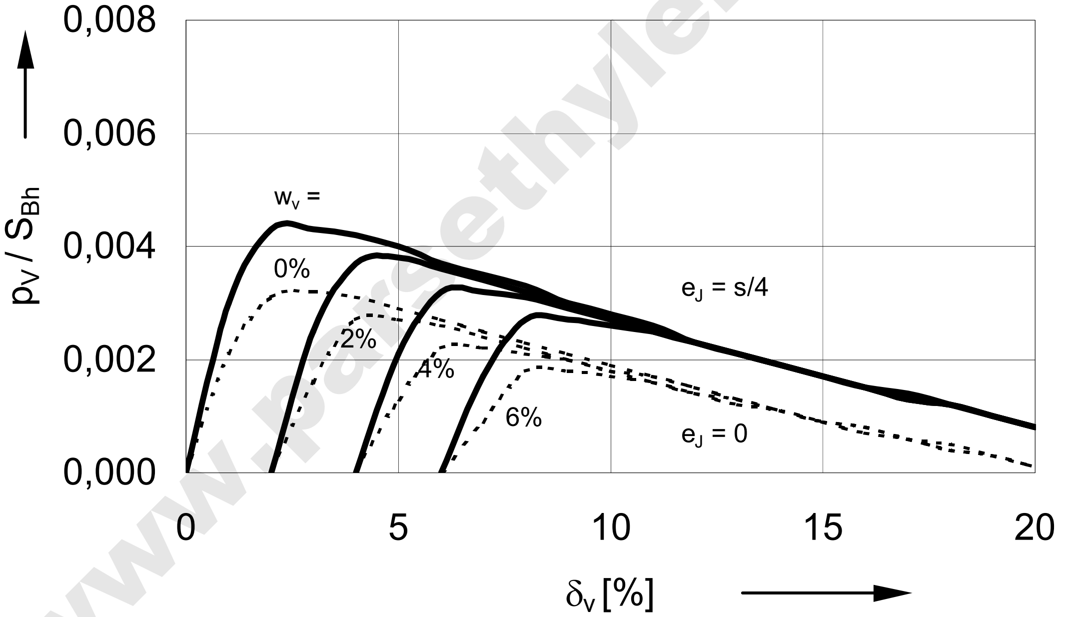


Diagram A6/4: **Load displacement curves of the four-link ring for earth loads q_v p_E = 20 kN/m², Soil Group 2; valid for S_{Bh} = 5 N/mm²**

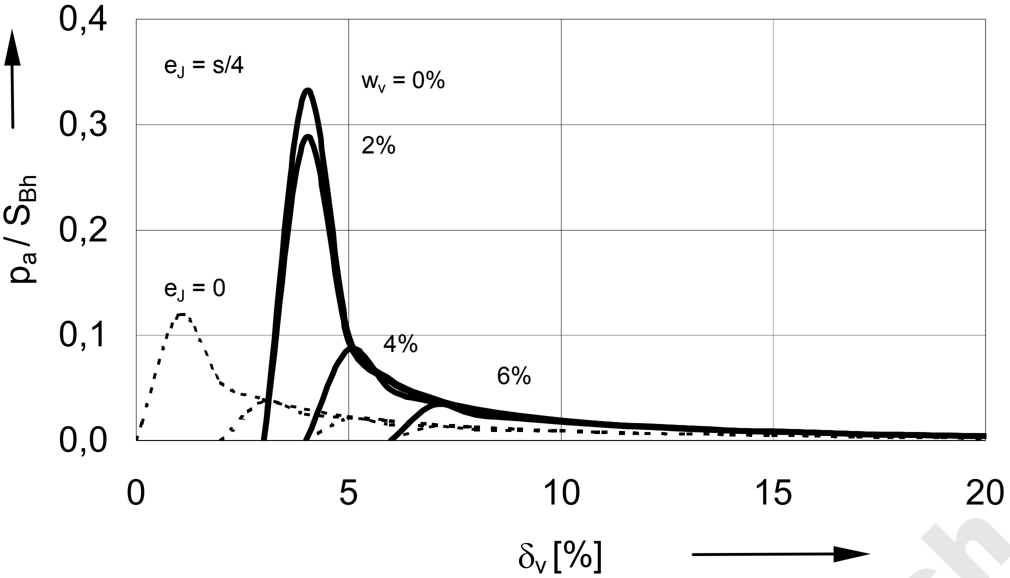


Diagram A6/5: **Load displacement curves of the four-link ring with external water pressure p_e p_E = 20 kN/m², Soil Group 1; valid for S_{Bh} = 5 N/mm²**

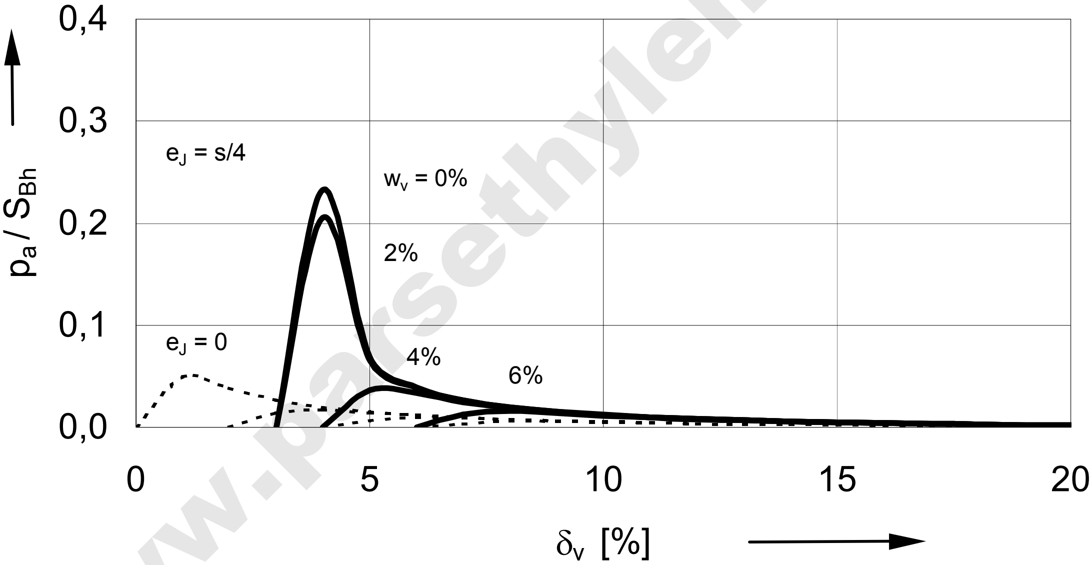


Diagram A6/6: **Load displacement curves of the four-link ring with external water pressure p_e p_E = 20 kN/m², Soil Group 2; valid for S_{Bh} = 5 N/mm²**

Appendix 7
Details on static calculation (Check list)

1. Old pipe

Material _______________

Geometry:

Circular profile	☐	Nominal width	DN	_________________	mm
Oval profile	☐	Diameter	B/H	_________________	mm
Other profile	☐	Precise dimensions and radii s. separate sheet			
			s	_________________	mm

General description of damage (comp. ATV-M 143-1):

Invert washout	☐	___________________________________
Longitudinal crack at crown	☐	___________________________________
Transverse cracks	☐	___________________________________
Fragment formation	☐	___________________________________
Pipe defects	☐	maximum elongation: _________________ mm
Other damage		___________________________________
		___________________________________
		___________________________________

Estimation of the bearing capability (mark as applicable):

Old Pipe Condition I:	old pipe alone capable of bearing	☐
Old Pipe Condition II:	old pipe-soil system alone capable of bearing	☐
Old Pipe Condition III:	old pipe-soil system no longer capable of bearing long-term	☐

General description of possible existing old pipe deformation:

____

____

____

2. Rehabilitation method ____

(Designation s. ATV-M 143-3) ____

Peculiarities ____

____

(e.g.: position of seam, U-point with U-liners, weakening through naps etc.)

3. Geometric liners

With circular profiles: mean radius r_L	____________________	mm
With oval profiles: mean crown radius	____________________	mm
Mean wall thickness s_L	____________________	mm

4. Material parameters of the liner

Liner material ________________________________

Modulus of elasticity of the liner, short-term ____________ N/mm^2

long-term ____________ N/mm^2

If required tensile strength σ_T, long-term ____________ N/mm^2

Bending tensile strength σ_{bT}, long-term ____________ N/mm^2

Bending compressive strength σ_{bC}, long-term ____________ N/mm^2

If required elongation at rupture ε_P ____________ %

5. Loads, soil characteristic values (With Old Pipe Condition III only and, possibly, to limit between Old Pipe Conditions I and II)

Traffic load ____________

Cover above pipe crown max h= ____________ m

min h = ____________ m

Soil in the pipeline zone

Elasticity modulus E_2 = ____________ N/mm^2

Angle of internal friction φ' = ____________ °

6. Effects

Groundwater above pipe invert max $h_{W,Inv}$ = ____________ m

Locally limited prestrain with circular profiles:

i.a.w. Fig.6a, depth: $w_v/r_L \cdot 100\%$ = ____________ %[1]

spread: $2\varphi_1$ = ____________ ° (usually 40°)

posn. φ_v (pipe invert = 180°) ____________ ° (usually 180°)

Locally limited prestrain with oval profiles

i.a.w. Fig. 9, depth: $w_v/r_L \cdot 100\%$ = ____________ %[1]

spread: $2\varphi_1$ = ____________ ° (usually 30°)

posn. φ_v = ____________ ° (usually ≅ 18°)[3]

Articulated ring prestrain ("ovalisation"

i.a.w. Fig. 6b, with Old Pipe Condition II or III):

$w_{AR,v}/r_L \cdot 100\%$ = ____________ %

Gap width i.a.w. Fig. 6c: $w_s/r_L \cdot 100\%$ = ____________ %

Heat effect: cooling $\Delta\upsilon < 0$ ____________ K

warming $\Delta\upsilon > 0$ ____________ K

Internal pressure: p_i = ____________ bar

Wall thickness divergence: $\Delta s_L/s_L \cdot 100\%$ = ____________ %

Possibly internal stress: σ_E = ____________ N/mm^2

1) Without precise measurements as a rule ≥ 2%
2) As a rule 0.5 % of the springer radius
3) As a rule in the centre of a flat range

Appendix A8/1 Calculation examples for the structural condition drawing-in of the pipe string

- **Example 1 (Case1)**

A liner DN 300 made from HDPE, Series 4 (PN 6) is reduced in cross-section at the edge of the trench and is drawn into a vitrified clay pipe.

Given: height difference h_{OC} = 1.8 m, trench length l_{OC} = 10m
total length of pipe section L = 100 m
friction coefficients $\mu_P \cong 0.1$ (rolling friction, if necessary confirmed in a test)
slope of old pipe $\varphi_P \cong 0°$, ground $\varphi_G \cong 0°$
clearance between old pipe and liner $\Delta h \cong 0$
liner: γ_L = 9.4 kN/m^3; $d_{L,e}$ = 355 mm; $d_{L,i}$ = 314.8; s_L = 20.1 mm
stress-dependent short-term E moduli:
σ = 3 N/mm^2; $E_{\sigma=3}$ = 970 N/mm^2; σ = 15 N/mm^2; $E_{\sigma=15}$ = 500 N/mm
lever arm for fixing in the reduction machine $a_2 \cong 1$ m

Material parameters, buckling limiting values:

$$R_{K,perm} = 1.34 \cdot \frac{(355 - 20.1)^2}{20.1} = 7477 \text{ mm} \qquad (5.1)$$

$$\varepsilon_{K,perm} = \frac{355}{2 \cdot 7477} \cdot 100\% = 2.37\% < 3\% \qquad (5.2), \text{ Table 3}$$

$$\sigma_{K,perm} = 13.4 \text{ N/mm}^2 \qquad \text{Table 3}$$

$$E_\sigma = 970 + \frac{970 - 500}{3 - 15} \cdot (13.4 - 3) = 564 \text{ N/mm}^2 \qquad (5.3a)$$

$$a = \frac{564 - 970}{970} = -0.4186 \qquad (5.4)$$

$$E_m = \frac{970}{3} \cdot \frac{-0.4186^3}{0.4186^2/2 + 0.4186 + \ln(1 - 0.4186)} = 657 \text{ N/mm}^2 \qquad (5.4)$$

Bending moments:

$$I_Q = \frac{\pi}{64} \cdot \left(0.355^4 - 0.3148^4\right) = 2.97 \cdot 10^{-4} \text{ m}^4 \qquad (5.6b)$$

$$M_{1,h} = 6 \cdot 657 \cdot 10^3 \cdot 2.976 \cdot 10^{-4} \cdot \frac{1.8}{10^2} \; 0 \; 21.1 \text{ kNm} \qquad (5.6a)$$

$$M_{2,h} = -21.1 \text{ kNm} \qquad (5.6a)$$

$$A_Q = \frac{\pi}{4} \cdot \left(0.355^2 - 0.3148^2\right) = 0.0211 \text{ m}^2 \qquad (5.7d)$$

$$\bar{g}_L = 0.0211 \cdot 9.4 = 0.199 \text{ kN/m} \qquad (5.7c)$$

$$\bar{g}'_L = 0.199 \cdot \frac{\sqrt{10^2 + 1.8^2}}{10} = 0.202 \text{ kN/m} \qquad (5.7b)$$

$$M_{1,g} = M_{2,g} = -\frac{0.202 \cdot 10^2}{12} = -1.68 \text{ kNm} \qquad (5.7a)$$

Bearing forces

$$\bar{A}_1 \cong \frac{21.1}{2 \cdot 0.355} = 29.7 \text{ kN} \tag{5.8}$$

$$A_1 = 29.7 - 0.202 \cdot \frac{10}{2} + 12 \cdot 657 \cdot 10^3 \cdot 2.97 \cdot 10^{-4} \cdot \frac{1.8}{10^3} = 32.8 \text{ kN} \tag{5.9}$$

$$\bar{A}_2 = \frac{21.1}{1.0} = 21.1 \text{ kN} \tag{5.10}$$

$$A_2 = 21.1 + 0.202 \cdot \frac{10}{2} + 12 \cdot 657 \cdot 10^3 \cdot 2.97 \cdot 10^{-4} \cdot \frac{1.8}{10^3} = 26.4 \text{ kN} \tag{5.11}$$

Tensile forces

$$Z_g \cong 0.199 \cdot 100 \cdot 0.10 = 1.99 \text{ kN} \tag{5.12a}$$

$$Z_M \cong (29.7 + 32.8 + 21.1 + 26.4) \cdot 0.10 = 11.0 \text{ kN} \tag{5.12b}$$

$$Z_\beta = 0 \tag{5.12c}$$

$$\Sigma Z \cong 1.99 + 11.0 + 0 = 13.0 \text{ kN} \tag{5.12d}$$

Stresses, pulling head

$$\text{Welding factor } \alpha_w = 1.0$$

$$\text{Net cross-section } Q_{Q,n} = 0.80 \cdot A_Q = 0.0168 \text{m}^2$$

$$\sigma_T = \frac{13.0}{0.0168 \cdot 1.0} = 774 \text{ kN/m}^2 = 0.774 \text{ N/mm}^2$$

Stresses on the old pipe (1)

$$W_Q = \frac{2 \cdot 2.97 \cdot 10^{-4}}{0.355 \text{ m}^3} = 1.68 \cdot 10^{-3} \tag{5.14b}$$

$$\sigma_T = \frac{13.0}{0.0211} + \frac{21.1 - 1.68}{1.68 \cdot 10^{-3}} = 616 + 11565 = 12181 \text{ kN/m}^2 = 12.18 \text{ N/mm}^2 \tag{5.14a}$$

$$\sigma_C = -11.56 \text{ N/mm}^2 \text{ (without N-component)} \tag{5.14c}$$

Elongation verification at the old pipe (1)

$$\varepsilon_T = \frac{12.18}{500} \cdot 100\% = 2.44\% < 3\% = \varepsilon_{perm} \tag{5.15}$$

$$\varepsilon_C = \frac{11.56}{564} \cdot 100\% = 2.05\% < 2.37\% = \varepsilon_{K,perm} \tag{5.16}$$

Elongation verification at the edge of the trench (2)

$$Z_2 = \Sigma Z - (A_1 + \bar{A}_1) \cdot \mu_P \cong 13.0 - (29.7 + 32.8) \cdot 0.10 = 6.75 \text{ kN}$$

$$\varepsilon_T = \frac{6.75}{0.0211} + \frac{1 - 21.1 - 1.681}{1.68 \cdot 10^{-3}} = 320 + 13550 = 13870 \text{ kN/m}^2 \qquad (5.14a)$$

$$= 13.87 \text{ kN/m}^2$$

$$\varepsilon_T = \frac{13.87}{500} \cdot 100\% = 2.77\% < 3\% = \varepsilon_{perm}$$

$$\sigma_C = -13.55 \text{ N/mm}^2 \text{ (without N-component)}$$

$$\varepsilon_C = -\frac{13.55}{564} \cdot 100\% = 2.40\% < 2.37\% = \varepsilon_{K,perm}$$

- **Example 2 (Case 2)**

A liner DN 300 made from HDPE, Series 4 (PN 6) is drawn into a concrete pipe DN 400 over a trestle at the edge of the trench.

Given: total length of the pipe section L = 100 m
friction coefficient μ = 0.1 (rolling friction if necessary confirmed in tests)
height difference: h_{OC} = 1.8 m
slope old pipe φ_P negligible. terrain $\varphi_{OC} \cong 0°$
liner: γ= 9.4 kN/m^3 ; $d_{L,e}$ = 355 mm; $d_{L,i}$ = 314.8 mm; s_L = 20.1 mm
old pipe: $d_i \cong$ 400 mm

Separation between old pipe and liner:

$\Delta h \cong$ 400 - 355 = 45 mm
$\Delta h/d_{L,e}$ = 0.045/0.355 = 0.127
$h_{OC}/d_{L,e}$ = 1.8/0/0.355 = 5.07

Minimum length of trench:

$$\min\left(\frac{l_{OC}}{d_{L,e}}\right) = 19 \qquad \text{Diagram A1/5}$$

$$\min\ l_{OC} = 19 \cdot 0.355 = 6.75 \qquad (5.17)$$

Bearing forces:

$$\frac{A_1}{\bar{g}_L} = 90 \qquad \text{Diagram A1/6}$$

$$\bar{g}_L = 0.199 \text{ kN/m} \qquad \text{see example 1}$$

$$A_1 = 90 \cdot 0.199 = 17.9 \text{ kN} \qquad (5.18)$$

$$\frac{A_2}{\bar{g}_L} = 50 \qquad \text{Diagram A1/6}$$

$$A_2 = 50 \cdot 0.199 = 10.0 \text{ kN} \qquad (5.18)$$

Appendix 8/2 Calculation example for the structural condition filling of the annular space

A HDPE liner, Series 4 (PN 6) is to be bonded in a DN 500 concrete pipe. By filling with water and adjusting the specific weight of the filler a subsidence of the liner on to the invert of the pipe is achieved (Case 2).

Given: annular gap between old pipe and liner 25 mm
water filling: γ_W = 10 kN/m^3
specific weight of the filler: γ_F = 8 kN/m^3
pressure height from slope of the old pipe: 0.25 m
+ additional overpressure with the injecting of the filler: 0.25 bar
liner: γ_L = 9.4 kN/m^3; $d_{L,e}$ = 450 mm; $d_{L,i}$ = 399; s_L = 25.5 mm
$\rightarrow r_L = 250 - 25 - s_L/2 = 212.25$ mm

Criterion for **subsidence**, Eqn. (5.19):

$$\Sigma F = 9.4 \cdot 0.0255 \cdot 2 \cdot 0.2122 \cdot \pi + (10 \cdot 0.399^2 - 8 \cdot 0.450^2) \cdot \frac{\pi}{4} \quad (5.19)$$
$$= 0.319 + 1.250 - 1.272 = 0.297 \text{ kN/m} > 0 \rightarrow \text{Case A}$$

Stress verification:

$$\gamma_F' = 8 \cdot \left(\frac{450}{424.5}\right)^2 = 8.99 \text{ kN/m}^3 \quad (5.21c)$$

$$\gamma_W' = 10 \cdot \left(\frac{399}{424.5}\right)^2 = 8.83 \text{ kN/m}^3 \quad (5.23c)$$

The load combination dead-weight (g) + water filling (W) is relevant for the stress verification. Assumption: rigid liner (= Bedding Case **I**)

relevant *bending moments* in the invert comp Appendix A2:

$$M_g = +1.500 \cdot 9.4 \cdot 0.0255 \cdot 0.2122^2 = +0.0162 \text{ kNm/m} \quad (5.20a)$$
$$M_W = +0.750 \cdot 8.83 \cdot 0.2122^3 = +0.0633 \text{ kNm/m} \quad (5.23a)$$
$$\Sigma M = +0.0795 \text{ kNm/m}$$

Combinations with the filling case (D) are not relevant here as M_F reduces the bending moment from g + W:

$$M_F = -0.750 \cdot 8.99 \cdot 0.2122^3 = -0.0644 \text{ kNm/m} \quad (5.21a)$$

Normal forces in the invert:

$$N_g = 0.500 \cdot 9.4 \cdot 0.0255 \cdot 0.2122 = -0.025 \text{ kN/m} \quad (5.20b)$$
$$N_W = +1.250 \cdot 8.83 \cdot 0.2122^3 = +0.497 \text{ kN/m} \quad (5.23b)$$
$$\Sigma N = +0.472 \text{ kN/m}$$

Cross-sectional values:

A = 25.5 mm^2/mm (6.19a)
W = 25.52/6 = 108.4 mm3/mm (6.19b)
α_{ki} = 1 + 25.5/(3 . 212.2) = 1.04; α_{ke} = 0.96 (6.18a,b)

Stresses:

$$\sigma_{bT} = +\frac{0.472}{25.5} + 1.04 \cdot \frac{79.5}{108.4} = +0.019 + 0.763 = +0.782 \text{ N/mm}^2$$

Short-term bending tensile strength of HDPE: σ_P = 21 N/mm^2 Table 2

Safety:

$$\gamma_{bT} = \frac{21}{0.782} = 26.8 >> 2.0 = \gamma_{nec}$$ Table 4

The necessary safety with stress verification is clearly exceeded.

Deformation:

Hardening time of the fuller : t $\cong$ 10 h
Average hardening temperature: $\upsilon \cong$ 40°C
Average material stress: σ = 2 N/mm^2

→ modulus of creep of liner material E_L (10h, 40°C) = 300 N/mm^2
(comp. creep curves of material used)

$$\Delta d_v \cong 0.1488 \cdot \frac{12 \cdot 0.297}{300} \cdot \left(\frac{212.2}{25.5}\right)^3 = 1.02 \text{ mm} \quad (5.24a)$$

$$\delta_v = \frac{1.02}{2 \cdot 212.2} \cdot 100\ \% = 0.24\ \% \quad (5.24b)$$

Deformation is to be taken into account as *prestrains* with the verification of the operating condition.

Stability verification:

Relevant load combination g + F + W + p_o (= 0.25 bar = 25 kN/m^2):

$$N_g = -0.500 \cdot 9.4 \cdot 0.0255 \cdot 0.2122 = -0.025 \text{ kN/m} \quad (5.20b)$$

$$N_F = -1.250 \cdot 8.99 \cdot 0.2122^2 = -0.506 \text{ kN/m} \quad (5.21b)$$

$$N_O \cong -(8 \cdot 0.25 + 25) \cdot 0.225 = -6.075 \text{ kN/m} \quad (5.22b)$$

$$N_W = +1.250 \cdot 8.83 \cdot 0.2122^2 = +0.497 \text{ kN/m} \quad (5.23b)$$

$$\Sigma N = -6.109 \text{ kN/m}$$

$$p_{e,exist} = \frac{\Sigma N}{r_L} = \frac{6.109}{0.2122} = 28.8 \text{ kN/m}^2 \quad (5.26)$$

$$p_{e,crit}\ (10h, 40°C) = 3.0 \cdot \frac{300}{12} \cdot \left(\frac{25.5}{212.25}\right)^3 = 0.130 \text{ N/mm}^2 \quad (5.25)$$

$$\gamma_{exist} = \frac{p_{e,crit}}{p_{e,exist}} = \frac{130}{28.8} = 4.51 > 2.0 = \gamma_{nec}$$ Table 4

The required safety against buckling is achieved during the filling.

Appendix 9
Calculation example for the service condition

In the following the calculation process for a HDPE liner and a hose liner are shown for the rehabilitation of a DN 500 old concrete and vitrified clay pipe.

The old pipe is carefully inspected beforehand so that quantitative statements on the prestrain are available. The stability verifications for the hose liner are listed for comparative purposes for the Old Pipe Conditions I, II and III.

The calculation process can be compared with the Advisory Leaflet through reference to formulas, tables, diagrams and nos. of sections.

Input data	**Dimension**	**Unit**	**Long pipe lining Old Pipe Condition I**	**Hose method**		
				Old Pipe Condition I	**Old Pipe Condition II**	**Old Pipe Condition III**
Old pipe						
Material	-	-	Concrete	Concrete	Concrete	Vitrified clay
Nominal width	DN	mm	500	500	500	500
Internal diameter	d_i	mm	500	500	500	500
External diameter	d_e	mm	600	600	600	581
Wall thickness	s	mm	50	50	50	40.5
Corrosion wear	Δs	mm	5	0	0	≈ 0
Bending tensile strength	σ_P	N/mm²	6	6	≈ 0	≈ 0
Bending compressive strength	σ_{dC}	N/mm²	>20	>20	>20	>20
Eccentricity of the old pipe joints	e_J/s	-	-	-	0.25	0.25
Liner						
Material	-	-	HDPE	UP-SF[3]	UP-SF[3]	UP-SF[3]
Radius (external)	$r_{L,e}$	mm	225	250	250	250
Wall thickness	s_L	mm	**22.5**	**9**	**10**	**9**
E-modulus, short-term	E_L	N/mm²	800	3000 [3]	3000 [3]	3000 [3]
long-term		N/mm²	110 [1]	1800 [3]	1800 [3]	1800 [3]
Bending tensile strength						
short-term	σ_{bT}	N/mm²	21 [2]	40 [3]	40 [3]	40 [3]
long-term	σ_{bT}	N/mm²	14 [2]	20 [3]	20 [3]	20 [3]
Necessary safety	$\gamma_{bT,nec}$	-	2.0	2.0	2.0	1.5
Bending comp. strength						
short-term	σ_{bC}	N/mm²	21 [2]	50 [3]	50 [3]	50 [3]
long-term	σ_{bC}	N/mm²	14 [2]	25 [3]	25 [3]	25 [3]
Necessary safety	$\gamma_{bC,nec}$	-	2.0	2.0	2.0	1.5
Imperfections						
Prestrain old pipe and/or liner	$w_v/r_L \cdot 100\%$	%	2	2	2	2 [4]
Position	φ_v	°	180	180	180	180 [4]
Opening angle	$2\varphi_1$	°	40	40	40	40 [4]
Gap width between old pipe and liner	$w_s/r_L \cdot 100\%$	%	0.5	1	1	1
Articulated ring prestrain (ovalisation)	$w_s/r_L \cdot 100\%$	%	-	-	3	6

Input data	**Dimension**	**Unit**	**Long pipe lining Old Pipe Condition I**	**Hose method**		
				Old Pipe Condition I	**Old Pipe Condition II**	**Old Pipe Condition III**
Soil						
Soil Group	G	-	-	-	3	3
Elasticity modulus for pipeline zone	E_2	N/mm²	-	-	8	8 [5)]
Internal friction angle	φ'	°	-	-	25°	25°
Cohesion	c	N/mm²	-	-	0	0
Effects						
Maximum height of ground-water above pipe invert	$h_{W,Inv,max}$	m	4.5	4.5	4.5	2.5
Unit weight of groundwater	γ_W	kN/m³	10	10	10	10
Unit weight of liner	γ_L	kN/m³	9.4	13.5 [3)]	13.5 [3)]	13.5 [3)]
Temperature change	Δ_υ	°C	-	-	-	-
Coefficient of thermal expansion	α_t	1/°C	-	-	-	-
Old Pipe Condition s II + III:						
Cover height	h	m	-	-	4	4
Traffic load	-	-	-		HGV 60	HGV 60
Area load	p_o	kN/m²		-	-	-

1) Comp. Table 2 (long-term modulus for 2 years) and extrapolation for 50 years

2) Comp. Table 2 and ATV-DVWK Standard ATV-DVWK-A 127E

3) Unsaturated polyester resin, synthetic fibre reinforced (UP-SF); assumed arithmetical value

4) The old pipeline is cracked *before* rehabilitation; application of w_v necessary for external water pressure only

5) For the example calculation it is assumed that the elasticity modulus in the pipeline zone E_2 = 8 N/mm² is taken from a soil experts report.

Section (Formula No.) Table No. Diag. No.	Dimension	Unit	Long pipe lining Old Pipe Condition I	Hose method Old Pipe Condition I		
	Liner					
	Mean radius r_L	mm	213.8	245.5	245	245.5
	Ratio r_L/s_L	-	9.5	27.3	24.5	27.3
	Local prestrain w_v	mm	4.3	4.9	4.9	-
	Articulated ring prestrain (ovalisation) $w_{AR,v}$	mm	-	-	7.35	14.7
	Gap width w_s	mm	1.1	2.5	2.5	1/0 [6)]
	Effects					
(6.13)	External water pressure above liner invert p_e	kN/m^2	45	45	45	25 [8)]
A 127E	Unit weight of the soil γ_S	kN/m^3	-	-	20	20
A 127E	.... under water γ_S'	kN/m^3	-	-	-	10
(6.7b)	Earth load p_E	kN/m^2	-	-	80	60
A 127E	Traffic load p	kN/m^2	-	-	12	12
A 127E	φ	-	-	-	1.2	1.2
A 127E	p_v	kN/m^2	-	-	14.4	14.4
	Load distribution					
(6.8)	S_{Bh}	N/mm^2	-	-	4.8	4.8
A 127E	K_2	-	-	-	0.2	0.2
(6.10a)	λ_P	-	-	-	0.75	0.75
(6.10a)	λ_S	-	-	-	1.08	1.08
(6.11a,b)	q_v	kN/m^2	-	-	74.4	59.4
(6.11c,d)	q_h	kN/m^2	-	-	17.9	13.2
(6.12)	K_2'	-	-	-	0.24	0.22
	Old pipe-soil system					
	Related to specific eccentricity e_J/s	-	-	-	0.25	0.25
A6/2	Max $(q_v/S_{Bh}) \cong$ max (p_E/S_{Bh})	-	-	-	0.037	0.027
(6.1)	$q_{v,crit} \cong p_{E,crit}$	N/mm^2	-	-	0.18	0.13
(6.4)	$\gamma_I = q_{v,crit}/q_v$	-	-	-	2.42	1.75
Table 4	$\gamma_{I,nec}$	-	-	-	2.0	2.0
	Intersectional forces from p_e					
(6.13)	External water pressure p_e	N/mm^2	0.045	0.045	0.045	0.025
	Bending moment coeff.					
	m-crown	-	- [7)]	+0.002	+0.004	+0.004 [9)]
	m-invert	-	- [7)]	+0.045	+0.055	+0.073 [9)]
	Normal force coefficient					
	n-crown	-	- [7)]	-	-	-
	n-invert *or:*	-	- [7)]	-	-	-
(6.14a)	lower limit min n	-	-	-1.1	-1.1	-1.1
(6.14b)	upper limit max n	-	-	0.8	0.8	0.8
	Bending moment M					
(6.15a)	crown	Nmm/mm	+3.1 [7)]	+5.4	+10.8	+6.0
(6.15a)	invert	Nmm/mm	+82.1 [7)]	+122.0	+148.6	+110.0
	Normal force N					
(6.15b)	crown	N/mm	-95.5 [7)]	-	-	-
(6.15b)	invert *or:*	N/mm	-92.7 [7)]	-	-	-
(6.15b)	Estimate min N	N/mm	-	-12.2	-12.1	-6.8
(6.15b)	max N	N/mm	-	-8.8	-8.8	-4.9

Section (Formula No.) Table No. Diag. No.	Dimension	Unit	Long pipe lining Old Pipe Condition I	Hose method Old Pipe Condition I	Hose method Old Pipe Condition II	Hose method Old Pipe Condition iii
	Cross-sectional values of the liner					
(6.19a)	Area A	mm^2/mm	25.5	9.0	10.0	9.0
(6.19b)	Resistance moment W	mm^3/mm	108.4	13.5	16.67	13.5
(6.18a)	α_{ki}		1.040	1.012	1.014	1.012
(6.18b)	α_{ke}		0.960	0.988	0.986	0.988
	Stresses from p_e					
(6.17a)	Crown, internal σ_i	N/mm^2	-0.39	-0.57	+0.23	-0.09
(6.17b)	external σ_e	N/mm^2	-0.46	-1.75	-1.85	-1.20
(6.17a)	Invert, internal σ_i	N/mm^2	+0.60	+8.17	+8.16	+7.71
(6.17b)	external σ_e	N/mm^2	-1.35	-10.29	-10.00	-8.81
	Stress verification for p_e (safety factors)					
(6.22a)	γ_{bT}	-	23.5	2.45	2.45	2.59
Table 4	$\gamma_{bT,nec}$	-	2.0	2.0	2.0	1.5
(6.22b)	γ_{bD}	-	10.4	2.43	2.50	2.84
Table 4	$\gamma_{bD,nec}$	-	2.0	2.0	2.0	1.5
	Intersectional forces from q_v					
(6.11b)	Vertical total load q_v	N/mm^2	-	-	-	0.0594
A5.1/5+ A5.2/5	Bending moment coeff. m-crown, invert	-	-	-	-	+0.025 [10)]
A5.2/8	Normal force coeff. n-crown, invert	-	-	-	-	-0.10 [11)]
(6.15a)	Bending moment M crown, invert	Nmm/mm	-	-	-	+89.5
(6.15b)	Normal force N crown, invert	N/mm	-	-	-	-1.5
	Stresses from q_v					
(6.17a)		N/mm^2	-	-	-	+6.54
(6.17B		N/mm^2	-	-	-	-6.72
	Stress verification for q_v (safety factors)					
(6.22a)	γ_{bT} ,$\gamma_{bT,nec}$	-	-	-	-	3.06>1.5
(6.22b)	γ_{bC} ,γ_{bCnec}	-	-	-	-	3.72>1.5
	Interaction p_e and q_v					
(6.22c)	Verification for flexural tension	-	-	-	-	1.01 ≅ 1
(6.22c)	Verification for flexural compression	-	-	-	-	0.87 < 1
	Deformation					
A5.1/10 + A5.2/10	Elastic deformation	mm	7.87 [7)]	-	-	-
	$\delta_{v,el}$	%	1.84	2.2	2.0	2.9 [12)]
	$1/2 \cdot (w_v/r_L) \cdot 100\%$	%	1.00	1.0	1.0	-
	$w_{ARv}/r_L \cdot 100\%$	%	-	-	3.0	6.0
	Deformation verification					
(6.20)	δ_v	%	2.84	3.2	6.0	8.9
6.5.2	Reference value for $\delta_{v,perm}$	%	10	10	10	10

Section (Formula No.) Table No. Diag. No.	Dimension	Unit	Long pipe lining Old Pipe Condition I	Hose method		
				Old Pipe Condition I	**Old Pipe Condition II**	**Old Pipe Condition iii**
	Stability verification (Safety factors)					
(6.13)	*Ext. water pressure* p_e	N/mm^2	0.045	0.045	0.045	0.025
	r_L/s_L	-	9.5	27.3	24.5	27.3
	Imperfections:					
6.3.1.1	$w_v/r_L \cdot 100\%$	%	2	2	2	2
D1	$\rightarrow$Reduction κ_v	-	0.90	0.68	0.70	0.68
	$w_{AR,v}/r_L \cdot 100\%$	%	-	-	3	6
D2	$\rightarrow$Reduction $\kappa_{AR,v}$	-	1.0	1.0	0.80	0.53
	$w_s/r_L \cdot 100\%$	-	0.5	1	1	
(6.27)	$\Delta\ w_v/r_L \cdot 100\%$	-	-	-	0	0.28[8)]
D3	$\rightarrow$Reduction κ_s	-	0.96	0.63	0.65	0.59
(6.25)	$\kappa_{v,s} \approx \kappa_v \cdot \kappa_{AR,v} \cdot \kappa_s$	-	0.86	0.43	0.36	0.25
(6.24)	α_F	-	15.87	36.9	33.9	36.9
(6.26)	S_L (long-term pipe stiffness)	N/mm^2	0.0107	0.0074	0.0102	0.0074
(6.23)	$p_{e,crit}$	N/mm^2	0.147	0.117	0.124	0.068
(6.29)	γ_I	-	3.26	2.60	2.76	2.72
Tab.4	$\gamma_{I,nec}$	-	2.0	2.0	2.0	2.0
	Vertical total load q_v	N/mm^2	-	-	-	0.0744
D4	Coefficient α_{qv}	-	-	-	-	1.92[13)]
(6.38)	$q_{v,crit}$	N/mm^2	-	-	-	0.222
(6.39)	γ_I	-	-	-	-	2.99
Tab.4	$\gamma_{I,nec}$	-	-	-	-	1.5
	Heat effects					
	$\Delta\upsilon$	K	0	0	0	0
(6.33)	p_υ	N/mm^2	0	0	0	0
(6.31)	$p_{\upsilon,crit}$	N/mm^2	-	-	-	-
(6.34)	γ_I	-	-	-	-	-
Tab. 4	$\gamma_{I,nec}$	-	1.5	1.5	1.5	1.5
	Dead-weights					
	g_L	N/mm^2	≈ 0	≈ 0	≈ 0	≈ 0 [14)]
(6.36)	α_F	-	-	-	-	-
(6.35)	$g_{L,crit}$	N/mm^2	-	-	-	-
(6.37)	γ_I	-	-	-	-	-
Tab. 4	$\gamma_{I,nec}$	-	2.0	2.0	2.0	2.0
	Interaction q_v and p_e					
Tab. 4	$\gamma_{I,nec}(q_v)$	-	-	-	-	1.5
Tab. 4	$\gamma_{I,nec}(p_e)$	-	-	-	-	2.0
s. above	$q_{v,avail}$	N/mm^2	-	-	-	0.0594
s. above	$p_{e,avail}$	N/mm^2	-	-	-	0.025
s. above	Coefficient α_{qv}	-	-	-	-	1.92
s. above	$q_{v,crit}$	N/mm^2	-	-	-	0.222
6.5.3.4	$w_s/r_L \cdot 100\%$	%	-	-	-	0 [6)]
D3	$\rightarrow$reduction κ_s	-	-	-	-	1.0
(6.25)	$\kappa_{v,s} \approx \kappa_v \cdot \kappa_{AR,v} \cdot \kappa_s$	-	-	-	-	0.43
(6.23)	$p_{e,crit}$	N/mm^2	-	-	-	0.117
(6.41)	Interaction verification	-	-	-	-	0.59 < 1

6) With Old Pipe Condition III the earth and traffic loads are set on the safe side with the gap width $w_s = 0$ (comp 6.3.2.1).

7) From electronic calculation (the coefficients of Appx. A4 for Old Pipe Conditions I and II do not apply for HDPE liners, comp. validity range with deviating values for E_L, Page A4/1).

8) Load case external water pressure: verification as for Old Pipe Condition II (here however: $W_{AR,v}/r_L \cdot 100\% = 6\%$, $w_s = 1\%$ of r_L plus link ring expansion i.a.w. Eqn. (6.27).)

9) The coefficient for groundwater are to be extrapolated for $W_{AR,v}/r_L \cdot 100\% = 6\%$ (to be calculated with the aid of curves for $W_{AR,v}/r_L \cdot 100\% = 0\%$ and 3%, Old Pipe Conditions I and II or electronically).

10) Interpolation of bending moment coefficient $m_q = 0.22 / 0.026$ with $S_{bH} = 2.5/5\%\ N/mm^2$ gives $m_q = 0.025$ with $S_{bH} = 4.8\ N/mm^2$.

11) Interpolation of normal force coefficient $n_q = -0.24 / -0.09$ with $S_{bH} = 2.5/5\%\ N/mm^2$ gives $n_q = -0.10$ with $S_{bH} = 4.8\ N/mm^2$.

12) Interpolation of vertical deformation with $\delta_v = 6.8 / 2.6\%$ with $S_{bH} = 2.5/5\%\ N/mm^2$ gives $\delta_v = 2.9\%$ with $S_{bH} = 4.8\ N/mm^2$.

13) Interpolation of the coefficient for $q_{v,crit}$ with $\alpha_{qv} = 1.0 / 2.0$ with $S_{bH} = 2.5/5\%\ N/mm^2$ gives $\alpha_{qv} = 1.92$ with $S_{bH} = 4.8\ N/mm^2$.

14) The dead-weight of the liner counteracts the external water pressure and, on the safe side, can be neglected here.