

9.0 Design for thrust

9.1 Introduction

Thrust forces are unbalanced forces which occur in a pressure piping system when water flow changes direction or velocity or when the pipeline is dead ended. In the general case, the thrust forces of primary importance are:

- Hydrostatic thrust resulting from internal pressure
- Hydrodynamic thrust resulting from change in momentum of fluid flow

Thrust can be extremely large for pipelines having high internal pressures or large directional changes and must be resisted to prevent separation of the joints near the thrust point.

For buried pipelines, thrust resulting from angular deflections at standard and beveled pipe joints is resisted by dead weight or frictional drag, and additional restraint is usually not needed.

For fittings, the restraint provided by dead weight and surrounding soil is usually supplemented by welding adjacent pipe joints to increase the dead weight or frictional resistance, or by providing concrete thrust blocks or collars to increase the dead weight or the soil bearing area. Reducers and lateral wyes are special cases where longitudinal thrust is often resisted by compression of downstream piping.

9.2 Hydrostatic thrust

Typical examples of hydrostatic thrust are shown in Figure 9.2-1. The thrust in dead ends, outlets, laterals, and reducers is a function of internal pressure, P , and cross-sectional area, A , at the pipe joint. The thrust at an elbow is also a function of deflection angle, Δ , and is given by

$$T = 2 PA \sin \frac{\Delta}{2} \quad \text{lb} \quad (\text{Eq. 9.2-1})$$

where $A = \frac{\pi D_j^2}{4}$
 D_j = pipe joint diameter

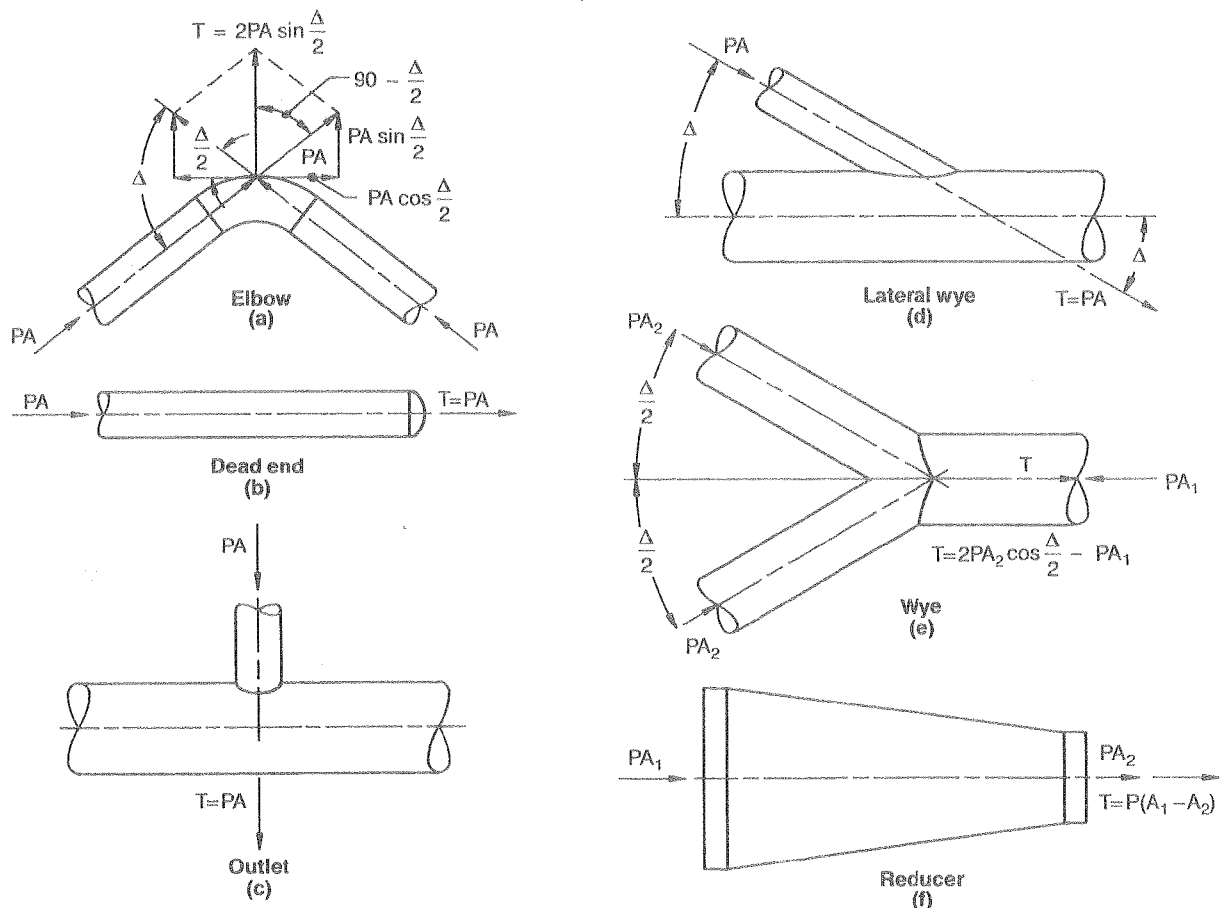


FIGURE 9.2-1. HYDROSTATIC THRUST, T , FOR TYPICAL FITTINGS.

9.3 Hydrodynamic thrust

Examples of hydrodynamic forces on elbows are shown in Figure 9.3-1. For a reducing elbow,

$$T = \rho Q \bar{V} \quad (\text{Eq. 9.3-1})$$

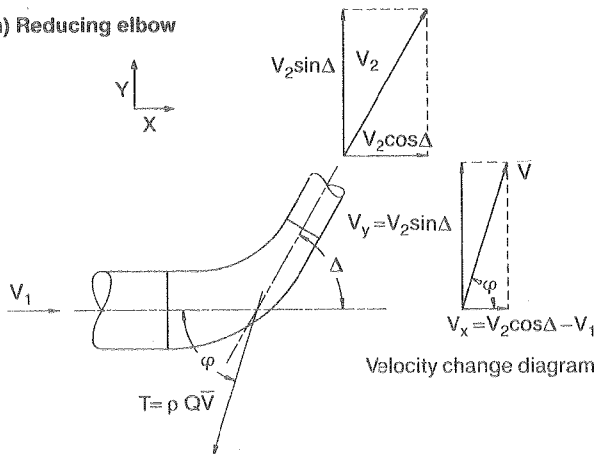
$$= \rho Q (V_1^2 - 2V_1 V_2 \cos \Delta + V_2^2)^{1/2} \text{ lb}$$

For standard elbows, $V_1 = V_2$ and Equation 9.3-1 becomes

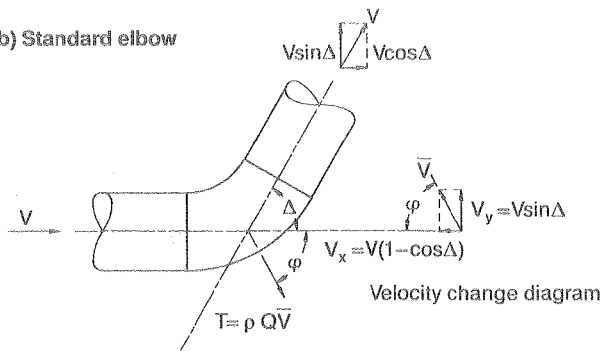
$$T = \sqrt{2} \rho Q V (1 - \cos \Delta)^{1/2} \text{ lb} \quad (\text{Eq. 9.3-2})$$

For flow velocities less than 10 ft/s, hydrodynamic thrust is small when compared to hydrostatic thrust and is usually ignored.

(a) Reducing elbow



(b) Standard elbow



- ρ = density of water, slug/ft³ (1.94 at 50°F)
- Q = volume flow rate, ft³/s
- V = velocity, ft/s
- Δ = elbow angle, degrees
- ϕ = angle of the hydrodynamic thrust, degrees

FIGURE 9.3-1. HYDRODYNAMIC THRUST AT ELBOWS. Thrust, T , acts on the elbow in a direction opposite to velocity vector, \bar{V} .

9.4 Thrust restraint at deflected joints

Thrust restraint is normally not required at rubber-gasket joints of beveled pipe or standard pipe installed with angular deflection.

Thrust, T , at deflected joints on long-radius horizontal curves is resisted by friction on the top and bottom of the pipe as shown in Figure 9.4-1. The total friction developed is equal to the thrust and acts in the opposite direction. Additional restraint is not required when

$$T \leq \mu L_p (W_p + W_w + 2W) \quad (\text{Eq. 9.4-1})$$

where $T = 2PA \sin \frac{\theta}{2}$

L_p = length of standard or beveled pipe, ft

μ = coefficient of friction

W_p = weight of pipe, lb/LF

W_w = weight of water in pipe, lb/LF

W = earth cover load, lb/LF

θ = deflection angle, degrees

The rough exterior surface of PCCP develops high frictional resistance between pipe and soil. For design, conservative values of μ vary from 0.3 for wet clay to 0.5 for gravel.

The earth cover load, W , may be computed from Marston's equation or, more conservatively, it can be assumed that W is equal to the weight of the prism of soil on top of the pipe:

$$W = w B_c H \quad (\text{Eq. 9.4-2})$$

where w = unit weight of backfill, lb/ft³

B_c = pipe outside diameter, ft

H = earth cover, ft

Uplift thrust at deflected joints on long-radius vertical curves is resisted by dead weight as shown in Figure 9.4-2. Additional restraint is not required when

$$T \leq L_p (W_p + W_w + W) \cos \left(\phi - \frac{\theta}{2} \right) \quad (\text{Eq. 9.4-3})$$

where $T = 2PA \sin \frac{\theta}{2}$

ϕ = slope angle, degrees

Downward thrust at deflected joints on long-radius vertical deflections is resisted by bearing on the bottom of the pipe. There is seldom need to investigate thrust in this direction for properly bedded pipe.

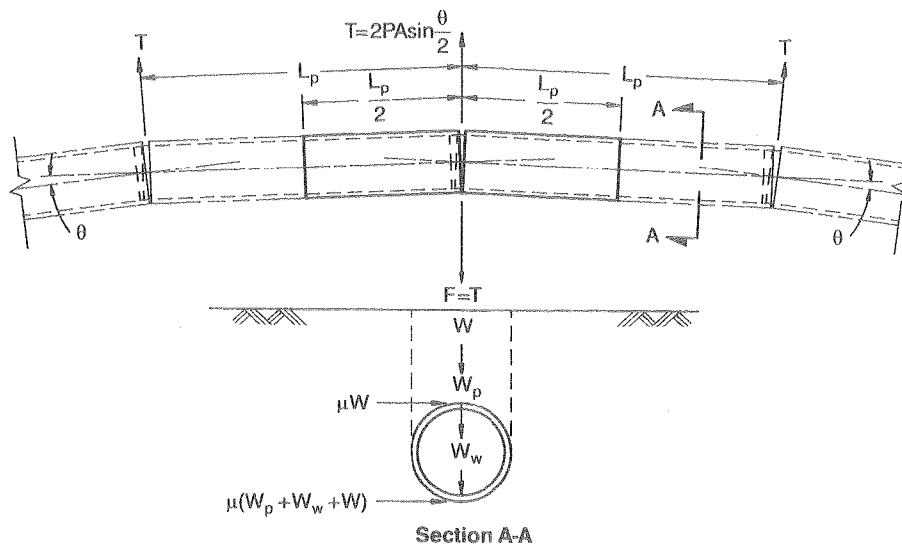


FIGURE 9.4-1. RESTRAINT OF THRUST AT DEFLECTED JOINTS ON LONG-RADIUS HORIZONTAL CURVES. Thrust, T , at each deflected joint is resisted by friction, F , developed on the top and bottom of the pipe along length L_p . The maximum frictional resistance per foot of pipe in a direction opposite to thrust is

$f = \mu (W_p + W_w + 2W) \text{ lb/LF}$, where μ = coefficient of friction; W_p = weight of pipe, lb/LF; W_w = weight of water in pipe, lb/LF; W = earth cover load, lb/LF. Movement of the joint will not occur when $T \leq f L_p$, where L_p is the length of standard or beveled pipe, ft.

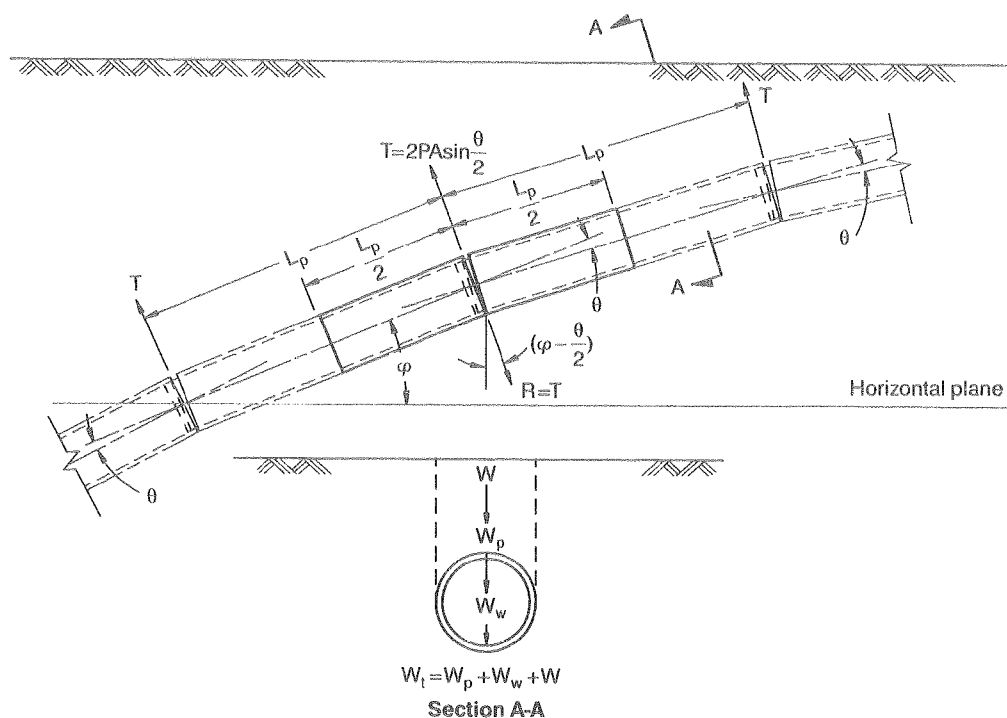


FIGURE 9.4-2. RESTRAINT OF UPLIFT THRUST AT DEFLECTED JOINTS ON LONG-RADIUS VERTICAL CURVES. Thrust, T , at each deflected joint is resisted by dead weight, R , developed by weight of pipe, water inside the pipe, and earth cover load along

length L_p . The maximum resistance per foot of pipe in a direction opposite to thrust is $r = W_t \cos(\varphi - \theta/2) \text{ lb/LF}$, and movement of the joint will not occur when $T \leq r L_p$.

9.5 Thrust restraint with welded joints

Additional thrust restraint at fittings or, if required, at deflected joints, can be provided by field welding a sufficient number of adjacent pipe joints. Figure 9.5-1 shows two types of field-welded joints for PCCP.

Thrust restraint with welded joints is designed in the following steps:

- Determine the total thrust to be resisted
- Calculate the required welded length of the pipeline
- Compute the required longitudinal steel area for each section of welded pipe
- Determine the size of fillet-weld required at each welded joint

Hydrostatic and hydrodynamic thrust can be calculated by the methods of Sections 9.2 and 9.3. For these calculations, the pressure should be taken as the field test pressure.

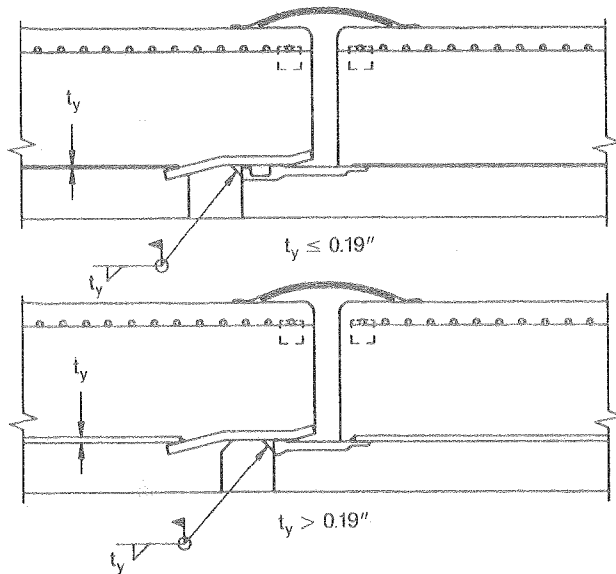


FIGURE 9.5-1. PCCP FIELD-WELDED JOINT DETAILS. For cylinder thicknesses of 0.19 inch or less, the concrete lining is held back at the bell during manufacturing to provide sufficient space for welding. For thicker cylinders, the grooved end of the spigot is cut off at the manufacturing plant as shown in the lower figure.

Thrust restraint with welded joints at dead ends and elbows is shown in Figures 9.5-2 and 9.5-3, respectively. The required welded length of the pipeline at dead ends is

$$L = \frac{T}{\mu (W_p + W_w + 2W)} \quad \text{ft} \quad (\text{Eq. 9.5-1})$$

where $T = PA$

Equation 9.5-1 can be used to determine the required welded length of the branch pipeline at horizontal tees and outlets where A becomes the cross-sectional area at the branch pipe joint. For horizontal deflections, the required welded length on each leg of the elbow to resist horizontal thrust is

$$L = \frac{T}{2\mu (W_p + W_w + 2W)} \quad \text{ft} \quad (\text{Eq. 9.5-2})$$

where $T = 2PA \sin \frac{\Delta}{2}$

For vertical deflections, uplift thrust T is resisted by dead weight developed along total welded length $2L$, and the required welded length on each leg of the elbow is

$$L = \frac{T}{2(W_p + W_w + W) \cos(\phi - \frac{\Delta}{2})} \quad (\text{Eq. 9.5-3})$$

where ϕ = slope angle, degrees

The required cylinder cross-sectional area at the first pipe joint from the dead end is

$$a_{s(\max)} = \pi D_y t_y = \frac{PA}{f_s} \quad \text{in}^2 \quad (\text{Eq. 9.5-4})$$

where D_y = cylinder diameter, in

t_y = cylinder thickness, in

f_s = allowable longitudinal stress, psi

from which

$$t_{y(\max)} = \frac{PA}{\pi D_y f_s} \quad \text{in} \quad (\text{Eq. 9.5-5})$$

The allowable longitudinal stress in the steel cylinder, f_s , should not exceed 13,500 psi at operating pressure or 16,500 psi at test pressure. For the remaining pipe sections within welded length L , the cylinder thickness is

$$t_y = \frac{(L - \ell)}{L} t_{y(\max)} \quad (\text{Eq. 9.5-6})$$

where ℓ = distance from the bulkhead

The required cylinder cross-sectional area of an elbow is

$$a_{s(\text{elbow})} = \frac{T}{2 f_s} \quad (\text{Eq. 9.5-7})$$

where $T = 2PA \sin \frac{\Delta}{2}$

from which

$$t_{y(\text{elbow})} = \frac{T}{2 \pi D_y f_s} \quad (\text{Eq. 9.5-8})$$

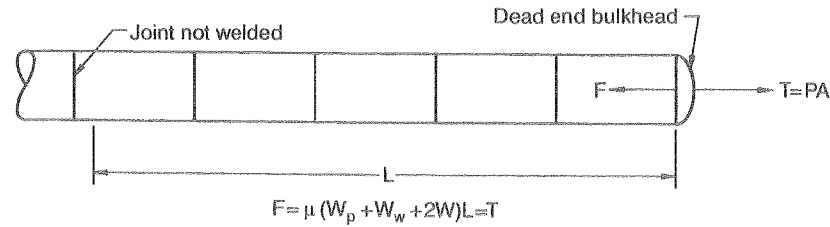
The cylinder thickness for pipe sections welded to each leg of the elbow is

$$t_y = \frac{(L - \ell)}{L} t_{y(\text{elbow})} \quad (\text{Eq. 9.5-9})$$

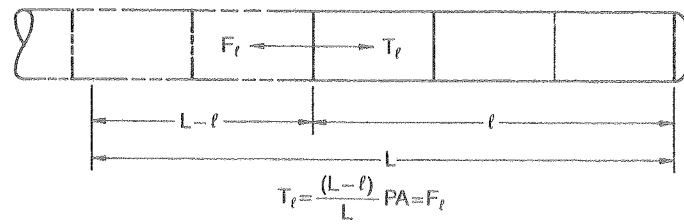
where L = length of welded pipe sections plus the tangent length of the elbow

ℓ = distance from the intersection of the elbow centerlines

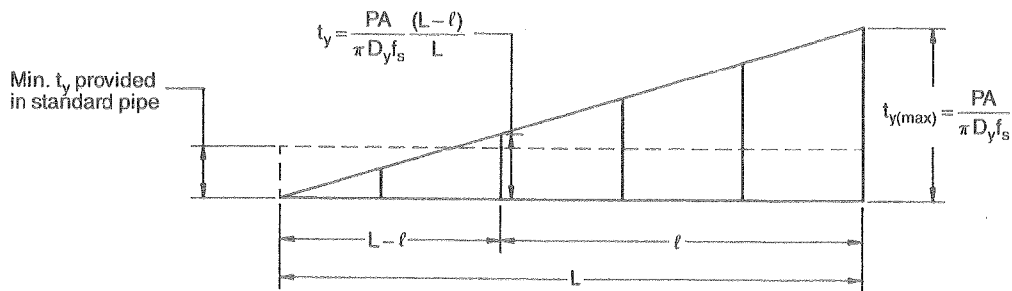
The throat of the fillet weld at each welded joint should be equal to the cylinder thickness but not less than 3/16 inch.



(a) Required welded length of pipeline, L



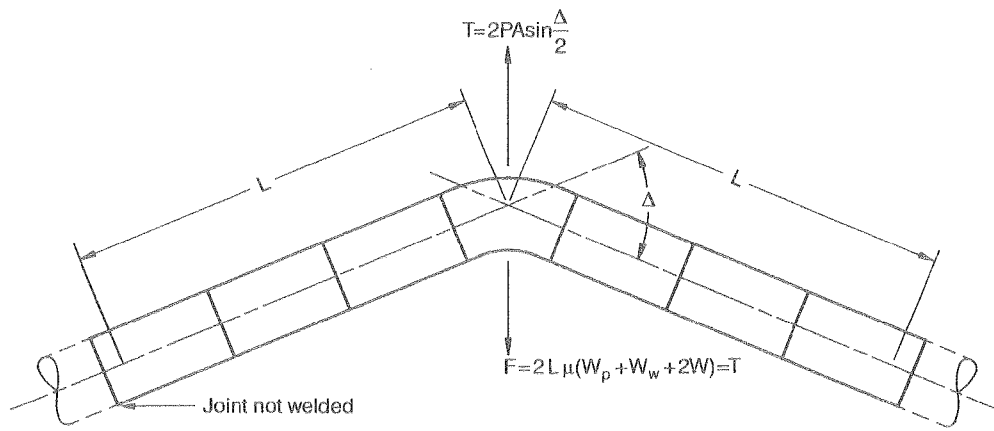
(b) Thrust at intermediate pipe sections, T_ℓ



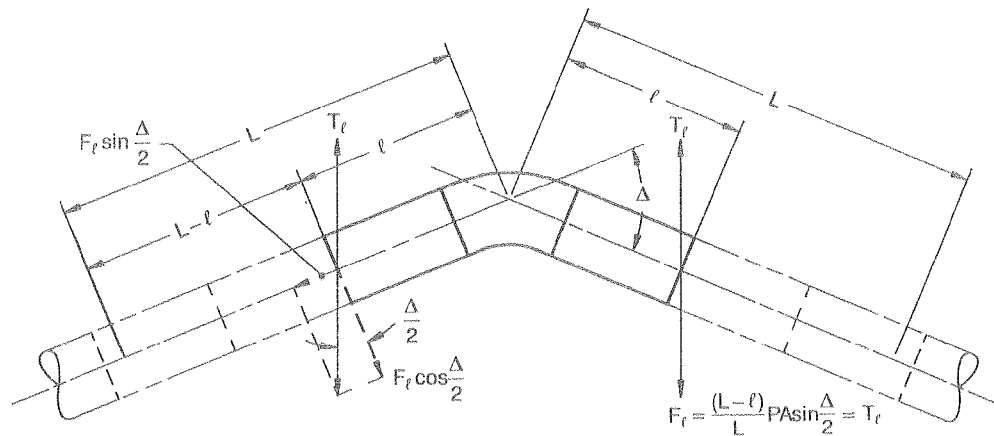
(c) Required cylinder thicknesses

FIGURE 9.5-2. THRUST RESTRAINT WITH WELDED JOINTS AT DEAD ENDS. Thrust, T , is resisted by friction, F , developed on the top and bottom of the pipe along length $L = \frac{PA}{\mu(W_p + W_w + 2W)}$.

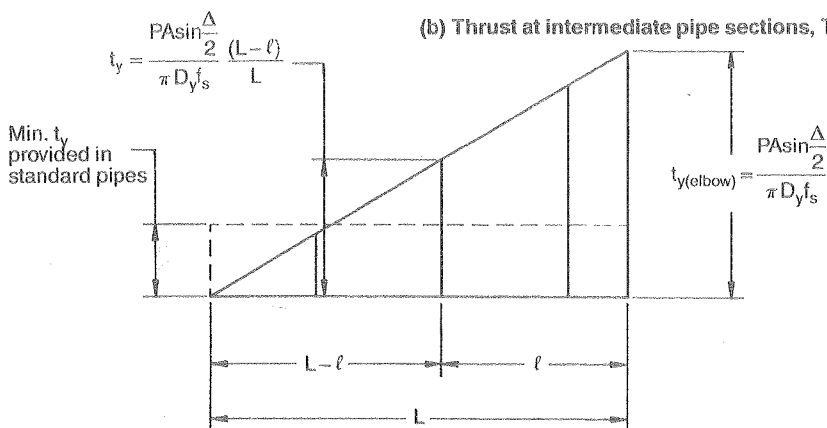
The required cylinder thickness at the first pipe section from the dead end is $t_{y(\text{max})} = PA / \pi D_y f_s$, where D_y is the cylinder diameter and f_s is the allowable longitudinal stress in the cylinder. $t_{y(\text{max})}$ diminishes linearly over the welded length, L , as shown in diagram (c).



(a) Required welded length of pipeline, $2L$



(b) Thrust at intermediate pipe sections, T_r



(c) Required cylinder thicknesses

FIGURE 9.5-3. THRUST RESTRAINT WITH WELDED JOINTS AT ELBOWS. Horizontal thrust, T , is resisted by friction, F , developed on the top and bottom of the pipe along length

$2L = \frac{2PA \sin \Delta/2}{\mu(W_p + W_w + 2W)}$. For intermediate pipe sections, the component of the frictional resistance along the centerline of the

pipe (tension) is $F_l \sin \Delta/2$ as shown in diagram (b). However, more conservatively, F_r is used to determine the longitudinal steel requirement and the required cylinder thickness of the elbow, $t_{y(\text{elbow})}$, is $\frac{PA \sin \Delta/2}{\pi D_y f_s}$. $t_{y(\text{elbow})}$ diminishes linearly over welded length, L , as shown in diagram (c).

9.6 Concrete thrust blocks

Concrete thrust blocks are usually classified as bearing type shown in Figure 9.6-1 or gravity type (anchor) shown in Figure 9.6-2. The bearing type block increases the

bearing area of a fitting against soil and the gravity type increases the weight of the fitting and pipe assembly.

Bearing type thrust blocks resist horizontal thrust or downward vertical thrust, and their design is based on the

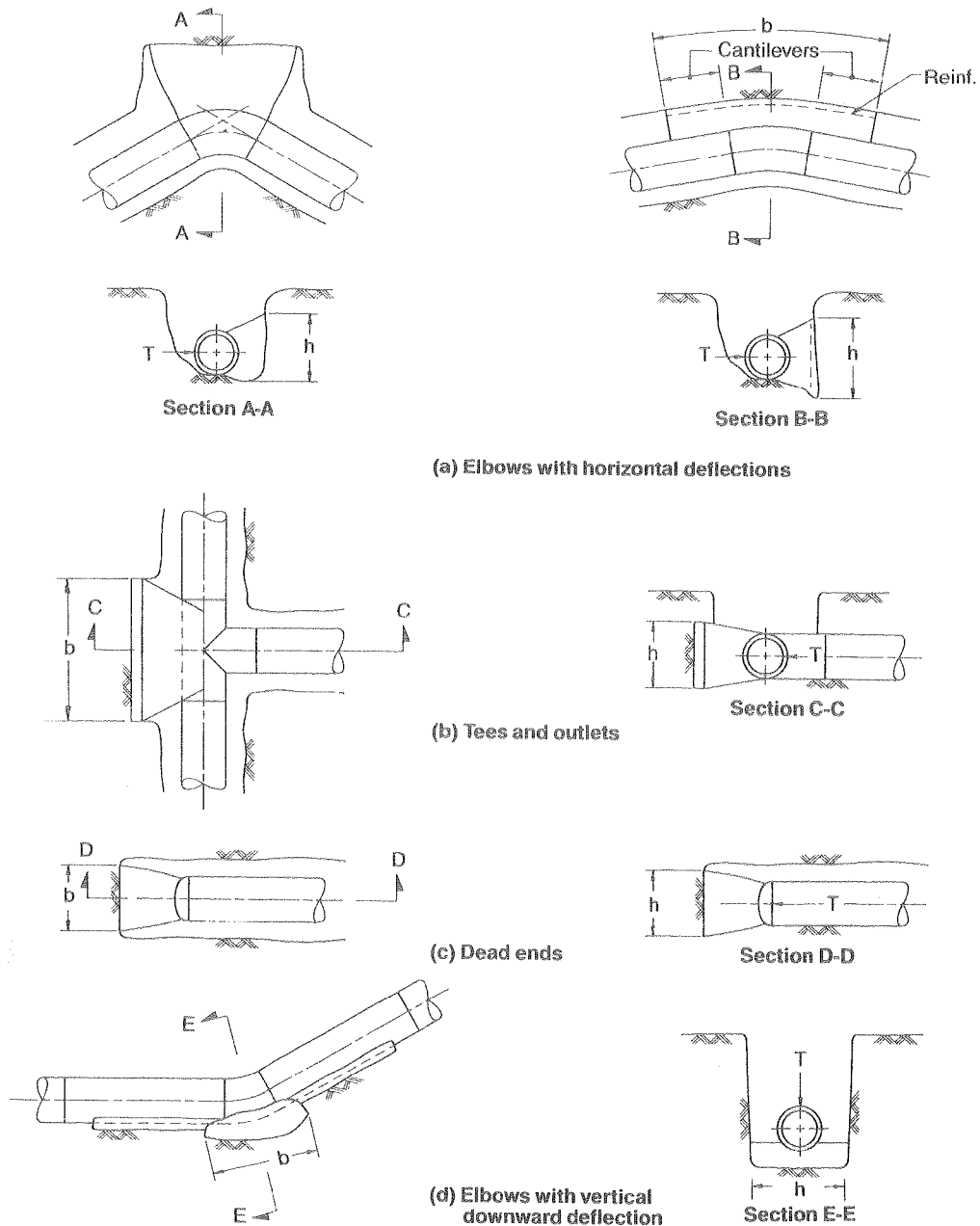


FIGURE 9.6-1. BEARING TYPE THRUST BLOCKS FOR TYPICAL FITTINGS. Unreinforced concrete thrust blocks should not extend beyond the joints of fittings. Where the extension is necessary, the two pipe sections adjacent to the fitting should be concrete

cradled as shown in diagram (d). Horizontal or downward vertical thrust is resisted over bearing area $b \times h$. For thrust designs requiring large bearing areas, structurally designed reinforced concrete thrust blocks should be used.

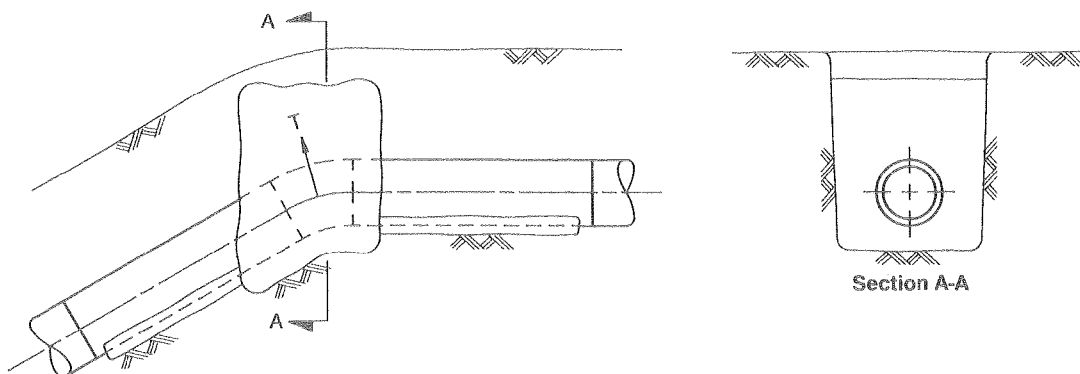


FIGURE 9.6-2. GRAVITY TYPE THRUST BLOCKS FOR ELBOWS. Vertical component of uplift thrust is resisted by the sum of the dead weights of the block, the elbow and attached piping, water

inside the elbow and attached piping, and earth cover over the elbow and attached piping.

support of the passive soil pressure behind the thrust block⁽¹⁾ or on the safe bearing capacity of the soil. The safe bearing capacity is dependent on the soil characteristics and depth of earth cover over the thrust block⁽²⁾ and varies from less than 1000 lb/ft² for soft soil to several tons/ft² for solid rock.

Thrust blocks should not be used if the soil behind the block may be disturbed by future excavation. Thrust blocks should be poured against undisturbed soil and centered vertically and horizontally about the direction of thrust, T .

9.7 Thrust collars

Reinforced concrete thrust collars are used to transmit thrust into undisturbed soil adjacent to the fitting instead of behind the fitting as shown in Figures 9.7-1(a) and (b). Thrust collars are cast around the pipe after it is installed.

In a valve chamber, the closed-valve (dead end) thrust can be transmitted from the pipe to the chamber wall through anchorage between the pipe and the wall as shown in Figure 9.7-1(c). If the wall anchorage area is not sufficient to transmit the thrust, a steel collar is usually welded around the pipe to increase the pipe anchorage surface area. Such chamber walls should be structurally adequate to take this thrust.

9.8 Design examples

Appendix G contains two examples illustrating thrust restraint at either deflected or beveled joints and thrust restraint with welded joints.

¹Tschebotarioff, G. P., "Foundations, Retaining and Earth Structures," McGraw-Hill, 2nd ed. 1973.

²Uniform Building Code.

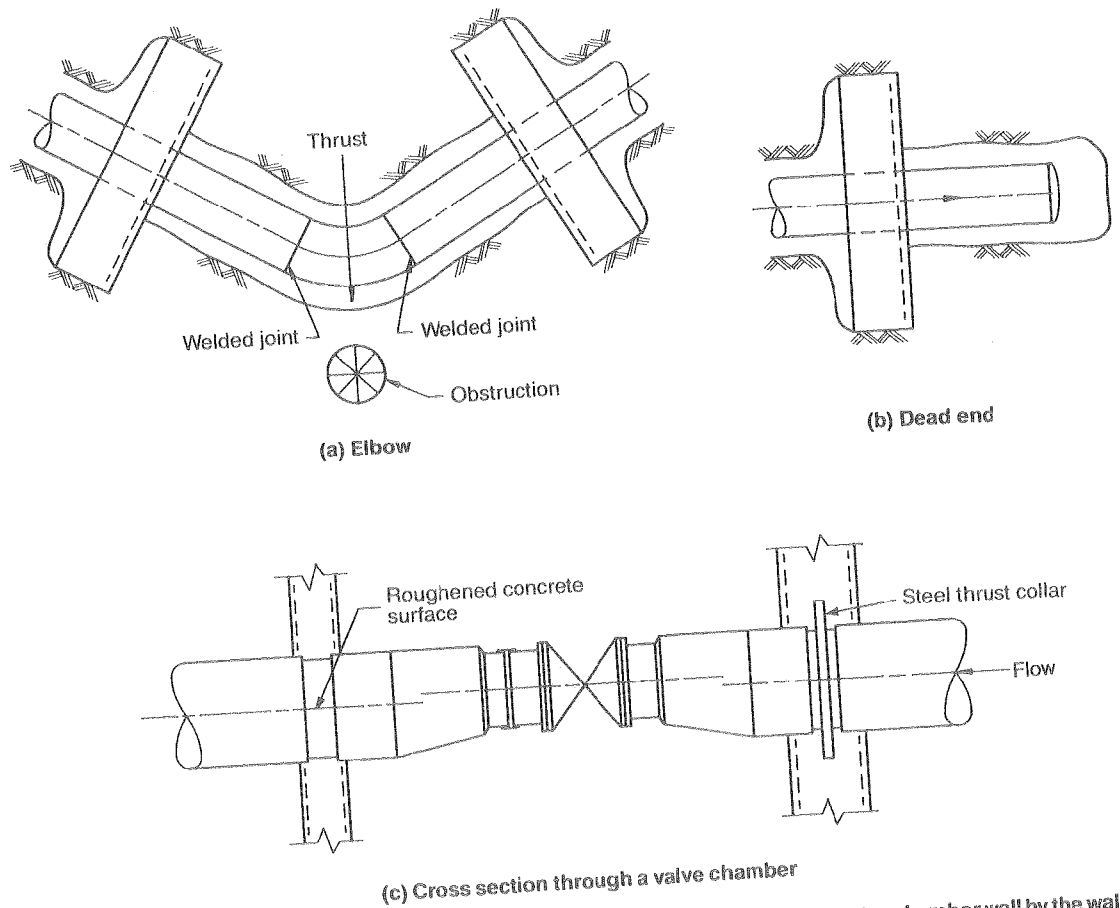


FIGURE 9.7-1. THRUST COLLARS FOR TYPICAL FITTINGS. Reinforced concrete thrust collars shown in diagrams (a) and (b) transmit thrust to undisturbed soil. In valve chambers, dead-end

thrust may be transmitted to chamber wall by the wall anchorage system shown at the left in diagram (c) and supplemented, if necessary, by a steel thrust collar shown at the right.

Condition	Criteria	Recommendations
Normal exposure	Noncorrosive environments	1, 2, 3 and 4
Sulfate soils	Soils containing more than 0.2% $\text{SO}_4^{=}$ or more than 2000 ppm $\text{SO}_4^{=}$ in soil pore water	1, 2, 3, 4 and 5
Acidic soils	Soil pH less than 5.0	1, 2, 3, 4 and 6
Low resistivity soils	High chloride soil subject to cyclical wetting and drying and with soil resistivity generally less than 1500 ohm-cm	1, 2, 3, 4 and 6
Stray current electrolysis	Prolonged discharge of direct current picked up from cathodic protection systems or other DC sources	1, 2, 3, 4 and 6 or 1, 2, 3, 4 and 7
Corrosive water conveyed	Water with a pH less than 5.5 or containing chemicals corrosive to concrete	1, 2, 3, 4 and 8
Subaqueous installations	Continuous immersion	1, 2, 3 and 4 or 1, 2, 4, 7 and 9
Atmospheric exposure	Continuous atmospheric exposure for more than 5 years	1*, 2, 10 and 11
Transition from buried to atmospheric exposure		1, 2, 3, 4 and 12
Connections to organically coated steel pipelines	Buried pipelines	13

* Shorting strap and electrical continuity not required.

Recommendations:

- 1 = Provide a steel shorting strap under the prestressing wire; apply cement slurry to the core at the time of prestressing and mortar coating; apply a 3/4-inch thick mortar coating over the prestressing wire; make all steel components in the pipe electrically continuous.
- 2 = Fill interior joint recesses with cement mortar.
- 3 = Fill exterior joint recesses with cement-mortar grout confined in polyethylene foam lined grout bands.
- 4 = Make all pipeline joints electrically continuous with low resistance bonds; provide test stations to monitor pipe potentials and current flow.
- 5 = Use portland cement containing not more than 5 percent tricalcium aluminate for all concrete and cement-mortar components.
- 6 = Coat the pipe exterior with a high build coal-tar epoxy.
- 7 = Apply cathodic protection.
- 8 = Line the pipe with polyvinyl chloride sheet.
- 9 = Coat steel joint rings with a high build coal-tar epoxy applied over an epoxy polyamide primer.
- 10 = Coat steel joint rings with a high-solids epoxy applied over an inorganic-zinc primer.
- 11 = Coat the pipe exterior with an acrylic latex; recoat as necessary to maintain coating integrity.
- 12 = Coat the pipe exterior with a high build coal-tar epoxy from 3 ft below to 1 ft above the ground surface.
- 13 = Electrically insulate the connecting pipelines.

FIGURE 10.1-1. RECOMMENDATIONS FOR PROTECTION OF PCCP IN CORROSIVE ENVIRONMENTS.