Thrust Restraint Concepts and Beam Loads for Segmented Pipelines at Bends

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ABSTRACT

Thrust restraint design of buried pipelines is dependent on the driving force distribution as well as pipe-soil interaction at the pipe-soil interface, which can be quite complex. The characteristics of the pipe-soil interaction are dependent on the piping configuration, pipe and soil mass properties, and internal and external loading, among other factors. It is generally recognized that a buried pipe has to move against the soil in order to develop maximum aggregate friction, adhesion, and lateral (passive) resistance forces, which in combination resist the unbalanced thrust forces. However, the design equations that are currently in use in the water/wastewater industry have been based on simplified assumptions that do not fully address the interfacial behavior, notwithstanding the recent AWWA M9 update.

Pipe deformations or movements, in particular, can also cause additional pipe stresses (axial, bending and shear) on the pipe and/or deflection in the joints at or near the unbalanced forces. These additional effects are typically not considered in the designs of water/wastewater pipelines using most of the current AWWA pipe design manuals. In addition, with numerous joint configurations having varying capabilities of axial and rotational movement (flexibility) along with the complex behavior of the pipe-soil interaction, the amount of movement the pipe bends can safely be subjected to without causing excessive stresses on the pipe or joint itself is generally unknown.

In 2010, the ASCE task committee on thrust restraint design of buried pipelines presented a draft White Paper that presented historical work, current practice and a preliminary framework for the design of thrust blocks and thrust restraint systems to improve current practice. Recognizing the widely different joint types used in practice, the white paper suggested this framework might eventually consist of two distinct design solutions: continuous (welded, fused or flanged) pipelines; and segmented (discrete) pipelines.

This paper presents some further work of the task committee towards improving understanding concerning the behavior and design of thrust restraint systems employing restrained joints for segmented pipelines. While this paper offers some more basic information and issues, it does not presume to dictate a common restrained length calculation method, nor does it dictate a specific new strength analysis for all the various varieties of segmented piping materials and joint restraints, including those used with concrete, ductile iron, fiberglass, polyvinyl chloride

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(PVC), and steel pipelines. Also, while it only focuses on horizontal bend situations, and with a case study of ductile iron piping (DIP) with only some quite adverse differential loading and support conditions, it does however present some principles that might eventually be extended to more detailed examinations of more well-supported bends and other thrust situations.

INTRODUCTION

During the first part of the last hundred years thrusts in pipeline construction with segmented pipes (defined here generally as non-restrained, gasket-sealed pipes, not welded or fused directly) were most often restrained by external restraining structures like concrete thrust blocks and reinforced concrete thrust walls. However, over the last few decades leading into the 21st century the industry has seen a marked increase in projects that instead employ for this purpose a certain number of special “restrained” joints strategically located within the pipeline itself. Reasons for this increasing utilization of restrained joints include increasing congestion in utility systems as result of burgeoning growth, increasing general size of pipelines (larger pipes often require huge blocks that are often less practical), and also availability of improved, modern restrained joint designs. These newer joint designs are in some cases much simpler, stronger, more flexible, and/or more available than those offered many years ago. In any case the function of the thrust blocks or a certain number of restrained joints in an otherwise non-restrained piping system is generally to distribute the thrust forces to the soil mass without excessive movement or failure of the pipeline.

When a designer, specifying utility and/or other parties, define the need for restrained joints to handle the issue of thrust restraint, the question then becomes how much (or minimum length of) restrained pipe should be installed at each thrust focus. The latter question ultimately affects the overall piping material package cost and in some cases also the progress of the project. The restrained joint pipes or fittings generally represent additional expense and perhaps in some cases less availability than the bulk of the simple, standard push-on or mechanically joined pipes and fittings.

In recent decades there have been many quite different design approaches used locally, or for different piping materials etc., to determine required minimum footage of restrained pipes. These different design approaches have sometimes resulted in substantially different lengths of restraint, for basically the same size, pressure and piping configuration conditions.

Until very recently virtually all prior approaches had in common that they were rather straightforward calculations, and most with simple free-body depictions. Once pertinent piping and soil conditions etc. became known for a project, these approaches could thus readily be applied by practitioners to determine the required minimum restrained length at locations in the pipeline. With the exception of a basic procedure and formula that has been used widely for many years in common by many entities including the ductile iron, PVC, and some proprietary pipe gland restraint industries, all other pipe materials basically had their own, somewhat different thrust restraint approaches.

The concrete pressure pipe industry sponsored development in the last few years of a new thrust restraint design procedure. In the recent M9 manual (AWWA 2008), a new thrust restraint design procedure was presented, based in part on “beam on elastic (lateral soil support) foundation” principles and verified by a finite element analysis. This method also checks in more detail than prior methods stress effects due to assumed loads, with some slight joint extension and bi-dimensional deformation of the (pipe) beam as applicable. It likewise considers separately effects of different structural joining conditions. In one case the individual pipe joints are mechanically harnessed together with slightly flexible connections, and in the other they are more rigidly welded together in the field.

CURRENT COMMITTEE STATUS AND EFFORT

There has been a yearning among responsible engineers for as much general agreement as practical in segmented pipeline thrust restraint design principles. A desire for more rigorous analysis involving the actual properties of the specific pipe, joint, as well as embedment and trench soil systems that might help further optimize or secure the designs, has also fueled the efforts of this task committee toward a more definitive guide to good practice. This is however a monumental undertaking when one considers all of the variables and different materials and structures involved.

With regard to basic behaviors of segmented pipelines and bends involving common restrained joints having at least some degree of flexibility, there has in the past been basic agreement that there is a driving force on the bend system with a resultant magnitude $T=2PA\sin(\Delta/2)$. Most methods use a most conservative thrust pressure area, e.g. as defined by the outside diameter of the pipe barrel in the case of DIP and PVC methods. While indeed there can be unbalanced pressure force pushing axially on the end of the first unrestrained pipe socket (sometimes far removed from the bend area by the entire provided length of restrained pipe), in the following analyses having to do with beam loadings we will however generally talk about slightly smaller inside pressure areas providing the beam loadings discussed. This is due to the fact that a small axial load, so far away, is unlikely to create the shear or bending effects examined in the immediate bend and adjacent pipe areas.

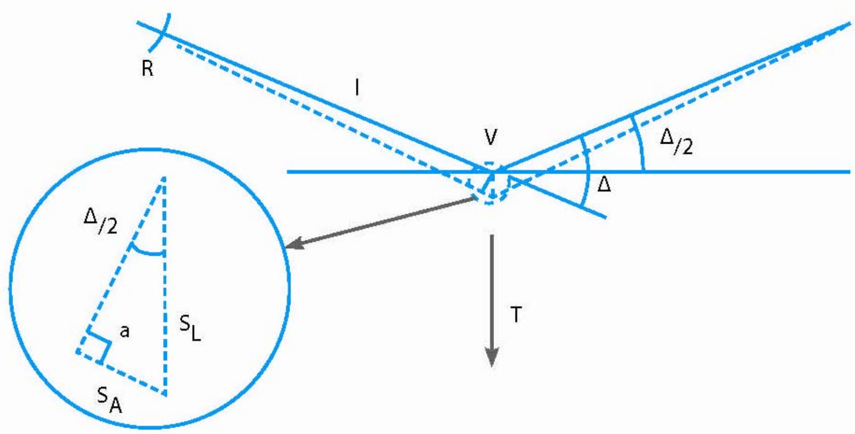
It is believed that there is intrinsic agreement that the bend and some length of adjacent piping will tend to move in the basic direction of that driving force, until enough available resistance is mobilized to offset and stabilize the driving force. With modern restrained joints of segmented pipelines, there is now further revelation in the collective industries that there is some available axial extension and rotational capability inherent to virtually all common joint designs. These capabilities effectively allow some relatively independent movements of an unblocked bend and adjoining pipe to occur in response to thrust loads.

When the soil envelope, strength and flexibility of pipe barrels and joining systems, and proximity to surrounding structures etc. will allow, there is increasing concurrence that quite high soil lateral resistances will be generated in many common pipe embedments. These lateral resistances occur most notably in the immediate pipe bend and adjoining pipe locations. Indeed, some researchers early on have even characterized this interaction as the restrained pipe system in effect becomes its own “thrust block”. This additional resistance is to some extent particularly quantified when one compares the required length results of prior procedures with the welded vs harnessed restrained joint requirements using the new AWWA M9 program. In reality this has also been traditionally demonstrated by the generally very good performance of unrestrained pipe joints that have been incidentally or purposefully deflected, at smaller deflection angles in much straighter sections of pressure pipelines.

In the latter case, the substantially laterally oriented thrusts due to small angle unrestrained pipe joint deflections or rotations can only be resisted by passive (lateral) soil pressure and lateral frictional resistances, as these most common pipe joints derive none of their claimed effectiveness nor stability from longitudinal frictional resistance (Kennedy, 1981). Attempting to subject any exposed or non-backfilled, unrestrained pipelines to high pressure will rather quickly demonstrate the unstable counterpoint of this. For such reasons, some standards consequently define that pipelines, and particularly when they employ segments of restrained joints, are most normally hydrostatically tested after backfilling (AWWA, 2006).

With regard to movement of a segmented restrained piping system, if the restraints of the surrounding soil envelope are disregarded, there can be rather pronounced movement of some bends in the direction of resultant thrust with even quite small amounts of axial movement or axial pipeline extension. Figure 1 depicts a most simplified derivation of a theoretical concept to approximate movement of a bend thrust focus purely as a result of an extension amount. If one assumes that there is an "S_A" amount of total axial movement in a given length of restrained pipe adjacent a bend, as shown in Figure 1 there would in turn per this theory be a predicted movement of the thrust focus in the direction of resultant thrust of the magnitude

$S_L = S_A/\sin(\Delta/2)$:



When rotation 'R' is small and the length (of pipe leg) 'l' is relatively long, angle 'a' approaches that of a right triangle. When leg 'l' is stretched or extended on amount 's_A' by a thrust force 'T', this means, due to the trigonometry involved:

Sin $\Delta/2 = \frac{S_A}{S_L}$ **And therefore, movement of thrust focus 'V'.**

or $S_L = \frac{S_A}{\sin \Delta/2}$

Figure 1. Geometry of Pipeline Bend Movement

Putting this into some perspective, if one is considering a 90 degree pipeline bend, a total extension amount of 0.25 inches (≈ 6.4mm) would represent a bend movement amount of 0.25 in./sin (90/2) or 0.35 inches (≈8.9mm). On the other hand, this same amount of extension at a 45 degree bend would represent a bend movement of 0.25 in./sin (45/2) or 0.65 inches (≈17mm). In practice, these developed relationships could well be more than theory. Researchers informed the Committee that their tests of actual 12" restrained ductile iron piping systems, with a type of strong pipe and a joint that did not allow any detectable extension at low pressures, exhibited in the most unimproved soil encasement conditions near precisely those amounts of measured movements at the bends when the legs of the 45 and 90 degree bend systems were caused to move axially one quarter of an inch.

What normally resists this movement is the soil mass interacting with and surrounding the restrained piping wherein the thrust forces are generated. Some researchers and design philosophies have traditionally factored these resistances as various distributions of simple Newtonian unit frictional (with others expanding on these principles as by Potyondy(1961)) and Rankine-type unit passive soil pressure resistances, whereas others are now looking instead at resistive concepts involving "elastic (soil) foundations" or "soil springs"(ALA, 2001).

It is reasonable to assume, and indeed is factored in to some extent in the new AWWA Manual M9 thrust restraint procedure or program, that some magnitude of internal beam stresses are also imposed on the pipe barrels and connections of restrained piping systems that are not thrust blocked. The new AWWA Manual M9 design procedure and programs often requires that the resulting bending moment be accounted for in the design of the pipes most near the thrust focus, to suitably resist some combined beam effects of the loading and resistances assumed.

In this regard, pipes of any material can be considered as basically hollow cylindrical beams. For conventional beam analysis, pertinent moment of inertia and section moduli properties about the neutral axis of a cross-section of at least homogeneous wall pipes like steel, ductile iron, pvc, and polyethylene e.g. can in turn be defined by the quite simple relationships:

$I_c = \pi(D_o^4 - D_i^4)/64$ and then $S = I_c/c$ or $S = I_c/(D_o/2)$ or $S = 2I_c/D_o$
Where,
I_c = Moment of inertia of the pipe cross-section about the axis of the pipe (in.^{4})
c = Distance from neutral axis to area of stress application (e.g. to extreme fiber, in.)
D_o = Outside diameter of the pipe (in.)
D_i = Inside diameter of the pipe (in.) and
S = Section Modulus of the Pipe (in.^{3})

Composite pipes generally require more complex analysis. Such constructions require unique determinations, by way of "modular ratios" and transformed areas etc. In some cases bond-dependent interactions between multiple composite components specific to the pipes constructions may also need to be considered.

Once the moment of inertia and section moduli properties of any beam are determined, it is possible to calculate simple extreme fiber shear (τ) and bending stress (σ_B) contributions due to same in the beam by the well-known relationships:

$\tau = [V/(\pi(D_o^2 - D_i^2)/4)$, with the denominator representing the pipe wall cross-sectional area, and
$\sigma_B = Mc/I$, where all variables are chosen with compatible units and,
τ = Shear stress
V = Shear load
M = Bending moment at the cross-section where bending stress is desired
c = Distance from neutral axis to extreme fiber
I = Moment of inertia of beam cross-section (e.g. centroidal, I_x , as mentioned above) etc.

Likewise, pipe beam deformations can be determined by manual calculations, providing that there is dependable knowledge of the loading and support conditions from the soil etc. These determinations also require dependable knowledge of the modulus of elasticity of the pipe material. Again, composite constructions make such determinations even more complicated, as do viscoelastic or plastic pipes with a stiffness that is greatly affected by duration of load application. Lastly, and similar to the M9 Manual approach (AWWA 2008), finite element analyses can alternatively be applied, that may be easiest with dependable software. However, appropriate output is much dependent on appropriate input of various pipe and soil parameters, along with a dependable value of Poisson’s ratio. Poisson's ratio is also time dependent in the case of viscoelastic (plastic) etc. pipes.

Pressurized pipes and bends are unlike conventional beam analysis in the structural field. The exact means and distribution of underground pipe thrust restraint “beam” load application, end restraints, deformations, and exactly how the thrust restraint pipe beam(s) are loaded and supported around the pipe beam by the soil is arguably much less understood. It is also less defined by published research with actual pressurized piping and presently available joints.

With regard to load application, the thrust driving and resisting forces and their distributions have been greatly simplified in the figures and assumptions of various methods. In some cases this is perhaps with little regard for the actual magnitude and distributions, and particularly so when inevitable movement occurs. While most methods depict for the driving force the “resultant” of pressure thrust ‘T’ exerted at a discrete point or thrust vertex (intersection point of the pipe leg central axes), in reality thrust loads and reactions to an unblocked restrained bend in a buried restrained joint piping system are more complex.

The traditional bend thrust magnitude derivation as shown in partial cross-sectional view in Figure 2 assumes that there is a thrust vector of the magnitude PA in line with the axis of both pipe legs. It also assumes that this pressure is effectively applied to a full projected cross-sectional area of the piping e.g. per the shaded, overlapping paths of Figure 2, and thus appearing to act on the outside walls of the bend and/or pipe. The resultant of the two “PA” force vectors, located at the outside vertex location and in the direction of bend movement, is therefore conventionally resolved by static (trigonometric) analysis or vector addition to $T=2P\sin(\Delta/2)$.

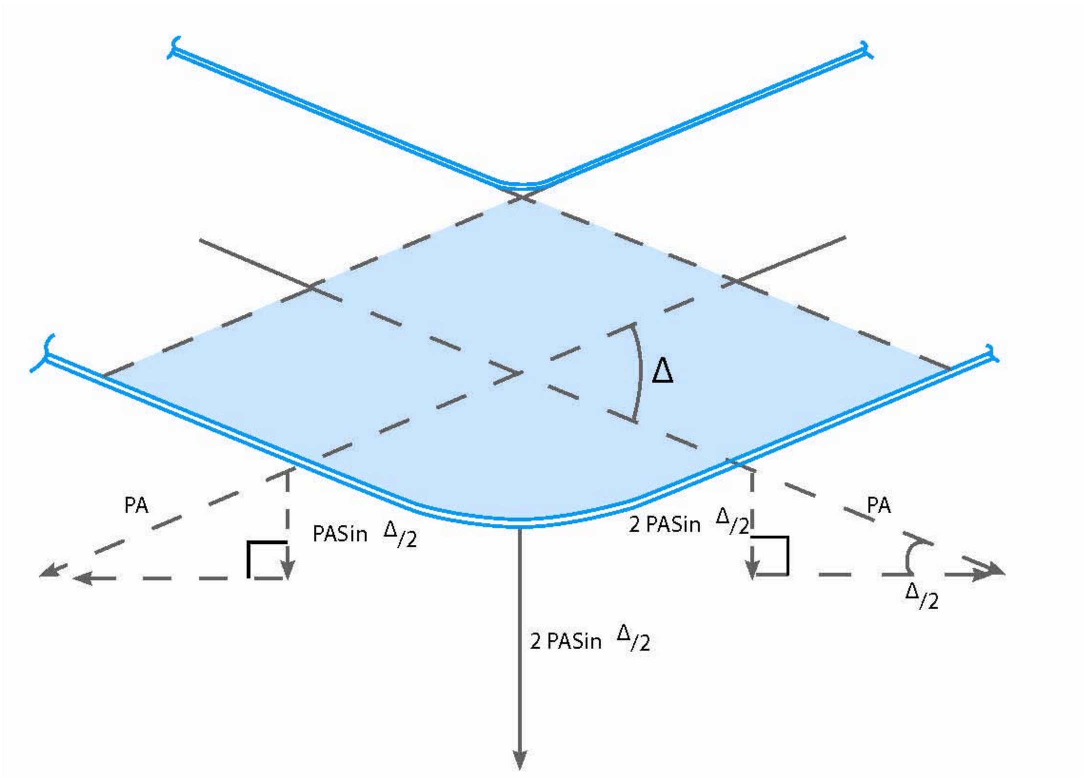


Figure 2. Traditional Derivation of Resultant Thrust at Bend

Per the fluid statics principle sometimes called the "second law" of Blaise Pascal, however, and disregarding normally much less significant momentum or hydrodynamic effects of flow, internal fluid pressure is said to act only normal to the surface of submerged e.g. pipe and fitting walls, and it is positive in the direction into the surfaces, as depicted in Figure 3. It can also be shown, though by more involved integration in accordance with this law, the resultant thrust force magnitude as derived and indicated in Figure 2 is correct.

Once the location and magnitude of driving force is established, this driving force imparted through underground restrained piping encounters reaction and resistance from the soil structure. As most restrained or harnessed joints used with modern segmented pipelines offer some degree of flexibility and/or extensibility, it is expected resistance is developed rather quickly and maybe even at relatively low pressures, particularly in the immediate bend area. While some traditional methods that depict a combination of passive soil reaction and frictional resistance assume that the maximum reaction is only available at a discrete point (that being the "vertex") in a free body depiction of the system, in reality it is the entire projection area of the bend fitting that bears immediately on the soil.

In the case of a particular 24" restrained 45 degree bend fitting design used often with ductile iron pipes, the "projected" length or footprint of even this rather compact bend transverse to the total resultant thrust vector shown in Figure 3 is more than 30 inches. The similarly projected planar area of the bend (not counting the bell protrusions) transverse to said resultant is more than 30 in.(D_o) = 30 in.(25.8 in.) = 774 in.^{2}, or a full ≈5.4 ft^2. To put this in some perspective, the traditionally determined thrust on a 24" ductile iron 45 degree bend fitting say at a 150 psi hydrostatic test pressure is 2 (150 lb/in.^{2}) (π (25.8 in.)^2/4) [sin 45/2 deg) or ≈60,000 lb.

Hypothetically backfilling the piping with a very good quality, well compacted soil with similar firmness to the native trench that results in a 4,000 psf bearing capacity, the resistance to just the bend movement would be in turn appear to be 5.4 ft^2 (4,000 lb/ft^2) or ≈22,000 lb. Thus, more than a third of the total resultant thrust might be resisted by bearing of just the compact ductile iron bend alone in at least such high quality embedment. Of course lesser quality embedment, or removal of soil behind the bend etc., would result in lesser support and more dependence on additional piping restrained length.

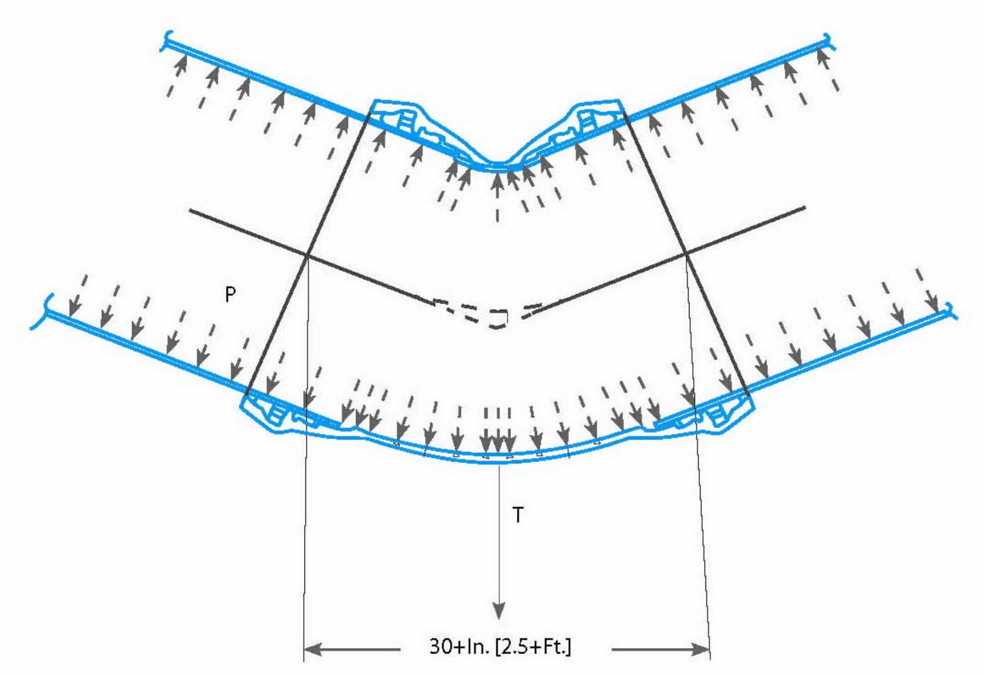


Figure 3. "Projected Length of 24" 45 Degree Compact Ductile Iron Restrained Bend

With increasing relative deformation of the soil behind a bend, some magnitude of shear force will be imparted at some point to each pipe end inserted into the bend. With further development and assuming the most severe traditional driving force analysis per Figure 2, it can be demonstrated hypothetically that absent any soil support behind the shaded pipe/fitting area a maximum shear force of the magnitude $V=PACos(\Delta/2)Sin(\Delta/2)$ would be exerted perpendicular to each piping leg. In the case of the 24" minimum Pressure Class 200 DIP and 45 degree bend arrangement at 150 psi test pressure e.g., this maximum shear force would be $V=(150\ lb/in.^2\pi\ (25.14\ in.)^2/4[Cos(45/2)Sin\ (45/2)]=$ ≈26,000 lb. If loaded in effective shear the cross-sectional wall area of a nominal PC200 DIP thickness pipe barrel available to oppose same per leg would be roughly

$\pi((25.8\ in.)^2-(25.14\ in.)^2)\ /4$ or ≈26 $in.^2$. Thus, the indicated shear stress contribution (τ) on the metal in such extreme case would be 26,000 lb/26 $in.^2$ or only ≈1,000 psi.

The following is another hypothetical calculation involving localized perpendicular load on the pipe end near the bend. If one assumes that a 20 ft long stick of this pipe adjacent the bend was also somehow held firmly enough on the half pipe length away from the bend, but with no earth behind the bend nor the nearest ten feet of adjacent pipe, a moment of 26,000 lb(10 ft) or 260,000 ft-lb would theoretically be generated at the mid-point of that pipe. This is a very severe loading and support condition that is not likely to occur in a buried flexibly joined system, unless perhaps the cases of some bending transitions of buried to exposed piping, or of unblocked bends with adjacent excavation and partial encasements of flowable fill or concrete, are considered etc. The bending stress at the extreme fiber (σ_B) in the middle of this pipe, as a result of that maximum bending moment at center, would as determined by the Mc/I relationship be 260,000ft-lb(12 in./ft)[(25.8/2) in.]/[π((25.8in.)^4-(25.14in.)^4)]/64] or ≈19,000 psi.

In a similarly hypothetical calculation, if one assumes a full PA of thrust is at the same time also pulling evenly and axially on that first pipe (with no soil support reducing the force) the tensile stress on the entire pipe wall cross-section as a result of that pull would be

(150 lb/in.^{2})π(25.14in.)^2 /4/[π((25.8in.)^2-(25.14in.)^2)/4)] or ≈2,800 psi.

Finally, a test pressure of 150 psi in a nominal thickness pipe will also create a tensile, circumferential hoop stress of the magnitude, σ = PD/(2t) = 150psi (25.8in.)/[2(0.33in.)] or ≈5,900 psi.

Superposition of localized maximum local tensile bending stress level (σ_B) of ≈19,000 psi with a uniform axial tensile stress of 2,800 psi would give a total maximum localized, axial tensile stress (σ_T) of ≈21,800 psi.

This example can now be further developed to obtain other stress values of interest. This includes the maximum tensile "principal stress"(σ_1) from a traditional Mohr's circle-type elemental analysis of normal (in this case hoop and thrust, or σ_B and σ_T) tensile and shear stress (τ) , for this hypothetical condition at the point in question as follows:

$$\sigma_1=1/2(\sigma_B+\sigma_T)+[(\sigma_B-\sigma_T)^2+\tau^2]^{.5} = .5(21{,}800+5{,}900)+[((21{,}800-5{,}900)/2)^2+1{,}000^2]^{.5} = 21{,}900 \text{ psi}$$

Even considering the assumed extreme lack of support (i.e. no support behind the bend or half the adjacent pipes), it would appear this localized principal stress in this example is below the general 42,000 psi tensile yield stress of ductile iron pipe material, and far below the maximum allowable apparent localized bending yield of 72,000 psi quoted for this material.

CONCLUSIONS

The ideas, examples and calculations shown in this paper are not an attempt to change the existing or in some cases long-standing length of restraint calculation procedures for all the various different piping materials explained in the prior White Paper. Nor are they an attempt to create a new wall thickness or other basic design of the piping involved. In this regard, at the present time no comprehensive research data has been offered that rigorously demonstrates exactly how the driving force is applied, and how all the various pipe beams interact with that driving force and all the myriad variables of soil loading and support.

Only the designer and actual field inspectors and practitioners know exactly what loads will be applied and what is actually around the pipes and fittings involved on their projects. The ideas and concepts of this paper are however tools that may help with further exploration and/or peace of mind (considering the extremely poor load/support conditions assumed) regarding some unknowns of designs or installation. Although a particular size and minimum class ductile iron pipe as well as unsupported bend configuration and pressure etc. has been used for the calculation example, piping of other configurations, sizes, thicknesses or materials etc. can be readily analyzed by these or other approaches, as can more favorable beam loading parameters and beam formulas, with soil support inserted specific and appropriate to the actual situations involved.

As Conner (1988) observed, some existing limited testing of actual buried restrained piping indicates that good quality embedment soils and compaction, will from a practical standpoint minimize movements and also substantially reduce the needed length of restrained joint piping. Particularly when accomplished in the immediate area of the unblocked restrained bend and adjacent pipes, such quality embedment will likely also reduce some structural demands on the pipes based on the examples provided above. Likewise, pipe material and/or third-party joint component manufacturers should also be consulted as to the deflection and extension etc. capabilities of the specific products to be used, as the presence of modern flexible joints etc. can limit the beam loads that are applied up the restrained pipe leg.

Additional research and study is required before any specific recommendations can be made. All preliminary conclusions and recommendations presented herein are preliminary and subject to change.

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