METAL WARS: WELDED STEEL VS. DUCTILE IRON FOR NEW LARGE DIAMETER RAW AND FINISHED WATER TRANSMISSION MAINS, A COMPARATIVE EVALUATION AND FIELD CASE STUDIES

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ABSTRACT
Final design of a new 5-1/4 mile 42- and 48-inch raw water transmission main is being performed for a Virginia water utility. Welded steel is less commonly considered for new large diameter transmission mains in the Eastern U.S., whereas it is more commonly selected in the Western U.S. Selection criteria scoring of 6 materials proved welded steel pipe (WSP) and ductile iron pipe (DIP) to be finalists for this project. The project’s material comparative evaluation will be presented, highlighting the following criteria, in priority order: i) total installed cost; ii) availability and demonstrated experience in required diameters and pressure classes; iii) life cycle cost; iv) failure mechanisms and history; and v) pre-purchase potential. For instance, it’s anticipated that DIP would need dielectric bonded coating to resist stray current, increasing the direct material component of its installed cost. The pipeline will be close to active quarrying operations and, thus, subject to seismic/blast loading ground conditions for several decades; the resulting project-specific pipe wall axial and bending stresses will be presented within the context of WSP versus DIP. Special cathodic protection necessary to accommodate stray current and soil corrosion potential will be discussed. Moreover, restrained joint systems for DIP and WSP will be compared. The second half of this presentation will feature field experience with large diameter raw and finished water transmission mains. Utility managers and operators will particularly benefit from a review of actual failure case studies and from a discussion of which lessons learned have manifested as changes to construction standards. For example, repeated failures of welded outlets on large diameter DIP has influenced the utility’s opinions for appurtenance configuration – it’s noted that the represented consultant advised a DIP manufacturer on suggested welded-outlet testing protocols, ultimately leading to improvements of its manufacturing process. These improvements will be discussed.

KEYWORDS

INTRODUCTION
In the world of metallic pipe, welded steel and ductile iron have many similarities yet their unique properties cause them to be designed and treated differently. Welded steel is less commonly considered for new large diameter transmission mains in the Eastern U.S., whereas it is more commonly selected in the Western U.S. Why are they designed differently? What are the cost drivers for each material? This paper presents many of the design and economic considerations of pipe selection and specifically outlines a comparative evaluation and design performed for a Virginia water utility.

DISCUSSION

Why Perform the Evaluation?
Patterned after pipeline material evaluations conducted for large diameter water transmission mains in the Western U.S., there’s a growing trend for owners and designers in the Eastern U.S. to perform a
similarly robust evaluation for projects with a significant (i.e. in the range of 60 to 70% of life cycle cost) first-cost investment. Current transmission main market competition lies between welded steel pipe (WSP) and ductile iron pipe (DIP) – a general definition for transmission mains are pipelines at least 24 inches in diameter. A robust evaluation outlines project performance requirements and assesses each material's ability to offer long-term reliability - commonly, an uninterrupted 100 year service life - at an acceptable, budgeted cost. Such an evaluation may challenge an owner's standards by bringing to bear current data and empirical evidence of failure modes, availability, and constructability, for both WSP and DIP. For example: repeated failures of welded outlets on DIP mains in Northern Virginia have spurred updates to construction standards; while larger staging areas are necessary to accommodate 50 foot typical WSP segment lengths.

The Design Process Begins with the Owner’s Standards
In the following design case, the Design Engineer advocated that an evaluation of a variety of materials be performed. Acknowledging that the Owner’s experience – and hence their construction standards – was exclusively with DIP, extra knowledge sharing and a study of regional market factors (e.g. Contractors with WSP experience) was necessary. This project serves as a design case study on the current state of the water transmission industry.

Design Case Study: Loudoun Water Raw Water Transmission Main Project
The project was the design of a new 5-1/4 mile 42- and 48-inch raw water transmission main from a high service river pump station to a water treatment plant. The project’s material comparative evaluation considered six pipe materials: ductile iron, welded steel, bar-wrapped concrete, PCCP, HDPE and PVC. Each material was scored under the following criteria, in priority order: i) total installed cost; ii) availability and demonstrated experience in required diameters and pressure classes; iii) life cycle cost; iv) failure mechanisms and history; and v) pre-purchase potential. Pre-purchase potential was eventually dismissed as an evaluated variable. Selection criteria scoring of the six materials proved WSP and DIP to be finalists for the project.

The Design Process Continues with a Dilemma for Bidding
In the case study example above the recommendation was to competitively bid DIP and WSP, to take advantage of a competitive market place to meet requirements with a minimum first-cost investment. Many successful DIP pipelines have been designed to AWWA M41 and many successful WSP pipelines have been designed to AWWA M11, but how should we specify each of these materials to take into consideration their differences and assure that the true cost of each is planned for? For instance, it was anticipated that DIP would need a dielectric bonded coating to resist stray current, increasing the direct material component of its installed cost. Relative to nearby quarry blasting, the two materials perform differently under the imposed strain these conditions and must be designed with these differences in mind. Moreover, different restrained joint systems and appurtenances are seen for DIP and WSP and must be well-defined before a comparison can be made.

Bid Documents Give Direction for Wall Thicknesses and External Coating
The two variables that most affect the choice between DIP and WSP, while also being the primary drivers of cost differences, are wall thickness and external coatings. Wall thickness gives the pipe its principal resistance to structural failure while an external coating is the leading means of corrosion protection from the pipe’s surrounding environment. While developing bidding documents, the engineer must define these two variables for each pipe type to ensure Contractor bids are based on two equally performing materials. Whether the winning bid is on WSP or DIP, the Owner must be satisfied with either material as defined in the bidding documents.
Wall Thickness
DIP and WSP are manufactured differently with DIP being centrifugally cast (the deLavaud process) and steel being spiral welded. DIP and WSP have similar ultimate and yield tensile strengths, but different elongation, hinting at a key difference between the two materials: the flexibility of WSP. In fact, WSP is categorized as a flexible conduit, while DIP is viewed as a semi-rigid conduit.

Ultimate Tensile Strength-Minimum Yield Strength-%Elongation
DIP: 60 ksi-42 ksi-10%
WSP: 60 ksi-42 ksi-22%

Given similar yield and ultimate tensile strengths, different elongations translate into different toughness ranges for the two materials – WSP offering greater toughness than DIP. In turn, different toughness ranges lead to material specific wall thickness design methods per AWWA, although methods for both consider the material’s resistance to internal loads (pressure design) and external loads to arrive at a required wall thickness. Owing to its long segment lengths, WSP wall thickness design also requires a handling check to evaluate its beam strength.

Internal Loads
The design methodology for both materials for internal loads use the Barlow Hoop Stress calculation to estimate wall thickness required to resist the maximum expected hoop stress from internal pressure – hoop stress is a circumferential tensile stress that is maximum on the pipe inner diameter. Application of the hoop stress equation to WSP and DIP, per AWWA methods, instills significant built-in conservatism such that computed wall thicknesses lead to relatively no likelihood that the minimum yield stress will be developed in the pipe wall due to static or surge pressure.

When designing WSP it should be noted that the welded restrained joints transmit pressure thrust forces through skin friction to the material backfilled against the pipe. This structural reaction prompts the need for a greater trench bedding envelope for WSP, as compared to that for DIP. For high pressure mains, WSP restrained welded joints transmit thrust forces over considerable distances to absorb force through skin friction; therefore, the strength of the weld must be evaluated to determine if it is adequate to transmit force from one pipe section to the next.

Regarding the Loudoun Water project, with surge suppression devices in place – air release and vacuum relief anti-shock values at each alignment highpoint as well as four specific non-high point locations, and a surge relief tank on the immediate discharge side of the proposed pump station – the maximum working and transient pressures are comfortably less than 200 psi closest to the pump station, and less than 150 psi for the majority of the line; hence, pressure class 150 and 200 DIP is the analytical solution for wall thickness. Accordingly, the equivalent WSP wall thickness to resist these internal pressures are 0.188 and 0.208 inches for 42 and 48 inch pipe.

External Loads
External load considerations for DIP include the calculation of ring bending stress and ring deflection to withstand overburden, traffic loads, and other external loads. DIP is relatively durable and loads from handling are not usually a consideration. Impacts such as blasting may require the evaluation of additional bending and axial stresses.

External load considerations for WSP differ from DIP. Bending stresses do not build up in steel pipe due to the material’s flexibility and thus its ability to readily transfer loads to the surrounding soils; however, if thin-walled WSP is specified pipe handling and the potential for pipe buckling under vacuum is greater in WSP and pipe thickness must be great enough to provide protection for these conditions. Impacts such as blasting may require the evaluation of additional bending and axial stresses for both WSP and DIP.
The greater stiffness of DIP may facilitate easier future tie-in connections since a stiffer pipe can better hold its roundness over time.

As applicable to the Loudoun Water project, DIP wall thickness to resist external loads is less than that specified above to resist internal pressure hoop stress, i.e. 150 and 200 pressure class DIP. Wall thickness required to handle WSP exceeds that required to resist external loads. However, the 0.188 and 0.208 inch WSP required to comfortably resist hoop stress from internal pressures affords sufficient thickness to resist external loading and to handle pipe segments without reservation.

Specified Wall Thicknesses for Bid Documents
To underscore a clear difference between current standards of practice in Western and Eastern U.S. geographies – relatively thin-walled transmission mains are common in the west as long as an external bonded coating and a cathodic protection system are specified. However, this standard is not as prevalently accepted for projects in the Eastern U.S. For the Loudoun Water project, while analytics proved DIP pressure class 150 and 200 and 0.188 and 0.208 inch WSP effective – with acceptable factors of safety built into these results – DIP thickness class 52 and its equivalent 0.3125 inch WSP are specified corresponding to the Owner’s standards. Cost implications of this decision can be highlighted by considering payment for pipe as$/lb of metal, verses the conventional $/linear foot of pipe. Applied to the thin-walled pipe, this payment is $/lb of metal required for performance; while payment for pipe defined in the bid documents is $/lb of metal specified. If thin-walled pipe is installed, whether DIP or WSP, it may be susceptible to being out of roundness at the time of future connections, which could increase the construction effort for future tie-in connections.

Corrosion Prevention
There is no shortage of varied opinion surrounding the need for, and choice of, corrosion prevention. The first step in determining the need for corrosion protection is obtaining profiles of soil resistivity measurements along the proposed alignment and comparing the results at the proposed pipe depth with documented soil corrosivity values. Widely used sources of corrosivity data include the Bureau of Reclamation (dominant in western U.S.), NACE/Corrosion Consultants (empirical; dominant in eastern U.S.), and DIP AWWA M41 Manual.

When other utilities, such as natural gas, are present in the vicinity of the proposed alignment, the designer should be alert to spikes in resistivity which may be produced by stray current from impressed current cathodic protection systems.

When potentially corrosive environments are presents the choices for the designer include galvanic anodes, impressed current, increased wall thickness, polyethylene wraps, bonded coatings, and any combination of these. Cost and reliability must be carefully weighed. Costs for bonded coatings may vary by manufacturer because one manufacturer is set up for it and the other requires a third party. Regardless of the variableness of the cost, bonded coatings will always be significantly more costly than polyethylene wraps. When it comes to reliability, polyethylene wraps certainly boost longevity when compared to bare pipe, but bonded coatings are still superior in this regard.

The AWWA M41 DIP Manual states that the use of PE wrap has “been found to be effective in mitigating the effects of stray current corrosion.” Owing to its excellent dielectric properties “that enable it to effectively shield ductile iron pipe from low-level direct current. Because ductile-iron pipe is laid in relatively short lengths that are electrically isolated by rubber-gasketed joints, stray current is not considered to be a particularly great hazard….in most cases, properly installed PE encasement applied
The United States Bureau of Reclamation posed the following questions to the National Academy of Sciences: Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils?; and: Will polyethylene encasement and cathodic protection reliably provide a minimum service life of 50 years?

After its study of the issue, the NAS concluded: “…polyethylene with cathodic protection provides a betterment to bare and as-manufactured ductile iron pipe with-out cathodic protection…” Designers with highly corrosive soil conditions will struggle to interpret this as an endorsement of polyethylene wrap. Under aggressive conditions where a bonded coating may be required, WSP may be more cost competitive relative to DIP.

**Welded Connections and Outlets**

The time and temperature controlled annealing operation of the deLavaud process causes DIP to be less suited to welded outlets, as welding heat stresses weaken the metal. Consequently, structural failures of welded connections and outlets are acknowledged. If welded connections or outlets are used, the manufacturer shall be consulted to discuss limiting the heat affected area of the parent pipe, restraining lateral joints, minimizing moment arm loads onto the weld. It’s noteworthy that one DIP manufacturer reinforces their welded connections/outlets, similar to the reinforcing collar and wrapper plates used on WSP welded connections/outlets. The represented consulting Engineer has helped a DIP manufacturer develop testing protocols for welded connections/outlets to evaluate resistance to moment arm failure.

**CONCLUSIONS**

In the Metal War of Welded Steel vs. Ductile Iron there is an exceptionally long list of pros and cons: DIP more readily accommodates field changes, is more competitive in constrained areas with many crossing utilities, has no mortar lining of field joints, is very competitive if pressure class pipe meeting M-41 is specified, requires a less robust bedding envelope and no welding.

WSP advantages include its custom engineered pipe wall, longer joints allow WSP to be more competitive in less constrained areas, its generally lower cost for corrosion protection (design dependant), and has no restriction for welded outlets.

The drawbacks of DIP include the significant cost of bonded dielectric coatings, a history of failure at welded outlets, restrained joints are costly in large sizes, and no industry standard exists for bonded coatings.

Likewise, WSP has its drawbacks and limitations such as the need for a more robust bedding envelope, accommodating a high pH at commissioning and very low flows, in low working pressure areas the
minimum wall thickness may be set by the handling requirements, and there will be a limited ability to modify alignment in the field.

In conclusion, it is hoped that the information presented here will inspire confidence to take a new look at a less-frequently used material, look behind your current standards and gain an understanding of the risks and rewards of a more analytical approach.

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