Conquering Construction Challenges during PCCP Rehabilitation

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ABSTRACT

Pipeline owners have completed many in-situ repairs of large diameter PCCP over the past several years utilizing fiber reinforced polymer composites (FRP). FRP is one of the most successful trenchless repair methods for full structural upgrade to specific pipe sections. During the design and field activities, owners, engineers and contractors at times encounter and have to work together to overcome challenges. One such problem is when the existing concrete substrate is not compliant with proposed Standard requirements. Through owner-engineer-contractor collaboration, design and construction solutions to resolve poor substrate conditions have been developed. In addition, innovative techniques for surface preparation of concrete and metallic substrates have resulted from tackling and overcoming these conditions. It is by sharing this knowledge and these concepts that the growing industry standard for FRP upgrades and repairs will be improved. This paper will provide up to date information on construction best practices, along with input on how to address substrate deficiencies.

BACKGROUND ON FRP REPAIR OF PCCP

In the United States alone, there are over 1.4 million miles of buried pipelines for water and wastewater municipal infrastructure (General Accounting Office, 2004). According to a recent study commissioned by AWWA (AWWA, 2011), approximately 25% of water mains greater than 10in are made of reinforced concrete or PCCP, with over $10 billion of PCCP assets in the United States alone. Fiber-Reinforced Polymer (FRP) linings are primarily used for targeted strengthening of large diameter pressure pipe, pipelines greater than 30 in. (760 mm), which has led to primary focus on PCCP for use of FRP linings.

PCCP has had a long and diverse history since its earliest application in the United States in 1942, with many changes in standards and materials over the years (Romer et al, 2008). There are two types of PCCP: lined-cylinder type (LCP), consisting of a steel cylinder with cast concrete core, wrapped with steel prestressing wire directly over the steel cylinder, and embedded-cylinder type (ECP) which has the prestressing wire embedded wrapped onto an outer concrete core, as shown in Figure 1. Site-manufactured ECP is made in larger diameters than LCP and has been constructed as large as 252 inches in diameter. Both types of PCCP are designed for the specific combination of internal pressure and external load in accordance with the procedures outlined in ANSI/AWWA C304, Standard Design of Prestressed Concrete Cylinder Pipe.

As shown in Figure 1, ECP-type PCCP is composed of an inner concrete core, a steel cylinder, an outer concrete core, prestressed wires which are wrapped around the outer core under tension, and an exterior mortar coating protecting prestressing wires from the environment. PCCP is designed for combined loads including internal working and transient pressure, pipe and water weight, soil load, and live load. The current analysis and design procedure is based on checking certain serviceability, damage, and strength limit states by calculating stresses and strains in the concrete core, mortar coating, steel cylinder, and prestressing wires (AWWA C304).

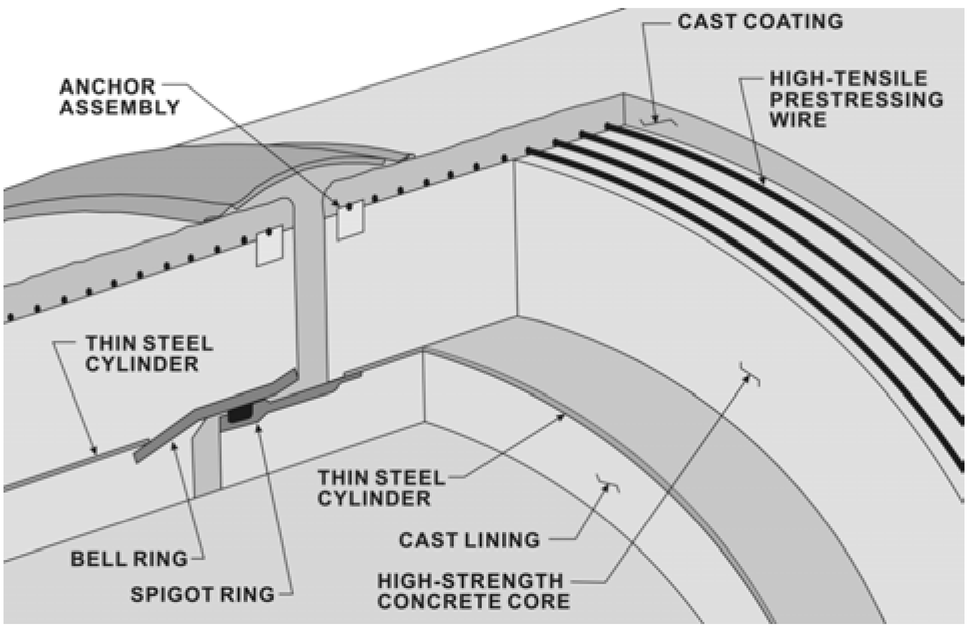

Figure 1. Cross section of a prestressed concrete cylinder pipe, ECP-type (Shenkirk, 2013)

There are a variety of failure mechanisms for PCCP; however, a typical failure mechanism involves breakage of the prestressing wires on individual sections of pipe (Romer et al, 2008). When prestressed wires on an individual section of pipe break, the structural integrity of that pipe is compromised and the risk of a failure in the line may be significantly increased, particularly if a pressure surge occurs in the line. In the late 1990's, electromagnetics technologies were developed to structurally assess the integrity of the prestressed wires on PCCP (Zarghamee et al, 2012). These inspections are able to isolate the location of broken prestressed wires with an accuracy that allows pipeline owners to identify individual pieces of pipe which have been structurally compromised. Based on over 2 million feet of PCCP electromagnetically inspected to date, the distress rate in PCCP is approximately 3.9%, with only a fraction of the distressed pipes having a significant number of broken wires (Higgins et al, 2012). Failure risk of pipes with broken wires can be performed and repairs can be prioritized. Once distressed pipe sections have been identified for rehabilitation, either replacement or a structural repair is selected based on various constraints related to accessibility to excavate, downtime, and cost.

FRP lining systems have been used increasingly for internal rehabilitation of water and wastewater pipelines since the mid-1990's. The primary motivation for use of FRP linings as a rehabilitation technology is minimizing disruption to the surrounding environment, particularly for distressed pipelines with difficult access to the exterior of the pipeline.

MAJOR FRP INSTALLATION OPERATIONS

The installation of an FRP structural liner inside the pipe includes many steps and operations, beginning with dewatering of the pipeline and implementation of ventilation and environmental controls, followed by surface preparation of the pipe substrate as well as cleaning and drying of the prepared pipe substrate. The procedure for installation of the FRP material includes mixing of epoxy and mechanical saturation of the reinforcing fabrics, priming the substrate with an epoxy primer and a layer of thickened epoxy, application of the saturated FRP to the inside of the pipeline substrate (as shown below in Figure 2.), implementation of end termination details for the FRP lining system, and finally cure of the FRP material.

Figure 2. Installed longitudinal layer of FRP

Appropriate implementation of each of these steps is critical for a FRP lining system to be installed successfully and achieve the desired long term service life (Gipsov and Pridmore, 2012). One of the most important procedures for the installation of the internal FRP structural liner is adequate preparation of the pipe substrate to achieve sufficient bond of the FRP liner material to the host pipe and allow for proper load transfer between the FRP liner and host pipe.

The installation of an FRP liner system for rehabilitation of pipe lines is considered a bond critical application. Bond is not only a function of adhesion, but also a function of substrate integrity itself. Confirmation of appropriate preparation of the substrate is achieved through ASTM D4541 bond testing. Sample panels of FRP are installed on prepared substrate and testing occurs using the ASTM procedure. Testing of the adhesion sample panels should both confirm the adequacy of the existing inner core concrete strength and confirm that satisfactory surface preparation has occurred that is in compliance with the new AWWA Standard (ANSI/AWWA CFRP, in preparation). Given the importance of bond and adequate surface preparation, it is essential that this step is carried out using appropriate means and methods to insure long term success of the FRP liner.

CONQUERING CONSTRUCTION CHALLENGES

Surface preparation is a key element of the installation process and can present many unique challenges. Special consideration is given to this step and best practices have evolved over the past several years.

In cases where a concrete substrate is being prepared, specifications typically call for ICRI profile of CSP-3 or greater to create an open pore structure and to remove all protrusions, sharp edges, and surface contaminants. Surface preparation can be performed using several methods which include water blasting, abrasive blasting or pneumatic sponge-blasting. Water blasting of concrete surfaces is acceptable, given the appropriate equipment is utilized at the pressures necessary to achieve the specified surface profile. If water blasting is selected, it is recommended that 40,000 psi equipment, operating at 30,000 to 36,000 psi is utilized to ensure proper profile of the concrete substrate is accomplished.

Attempting to use lower pressure water blasting may result in low bond strength and could be a detriment to the long term integrity of the FRP system. Water blasting typically consists of hand-held or automated tooling, as shown in Figure 3, which positions the tip of the wand or wands 2-3 inches from the pipe surface. This type of equipment typically uses 6-10 gallons of water per minute, which is collected and managed as part of the installation process.

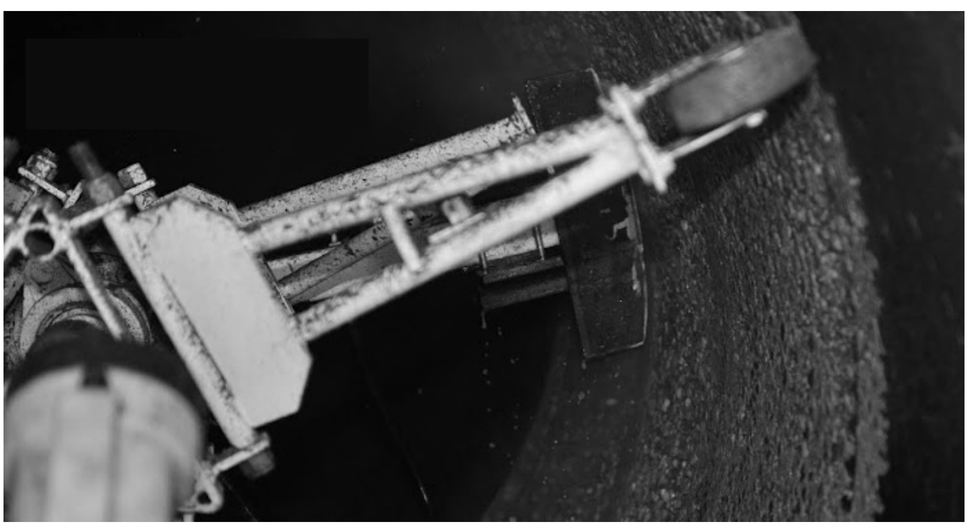

Figure 3. Surface preparation using water blasting equipment

One caution regarding high pressure water blasting is concern for over-blast. As seen in Figure 4, water blasting the surface opened up the substrate to allow for mechanical bond however also removed a significant portion of the cement paste in the process. Given the forces utilized during high pressure water blasting, over-blast of the surface, which adds time and construction costs associated with restoring the profile prior to installation of the FRP liner, needs to be mitigated. It is suggested that only experienced operators conduct this activity during the installation process. Due in part to concerns regarding risk of over-blasting the substrate, some installers have elected to shift to alternate surface preparation methods to mitigate this potential issue.

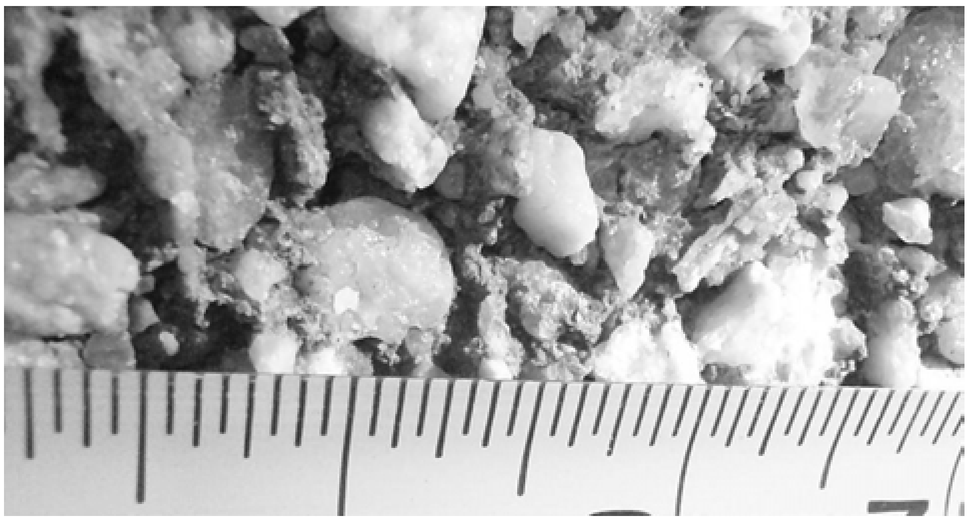

Figure 4. Close up of water-blast prepared substrate of inner core

Abrasive blasting is another method for preparation of the surface. Conventional methods of abrasive blasting include grit blasting and sand blasting and are completed using abrasive blasting equipment which has been modified for use inside a pipeline. Special precautions regarding mitigating airborne particulate levels are taken for this type of surface preparation in a confined space.

A special type of abrasive blasting, which has displayed positive results for pipeline applications, is sponge-blasting. Sponge media is open- celled, water based polyurethane impregnated with abrasives and is applied to the substrate using hand held or automated equipment as shown in Figure 5. On impact with the surface, the sponge particles compress and slide across the substrate producing a scrubbing action, more similar to a sanding effect, but eliminating the harsher and dustier negative effects associated with conventional grit blasting. The abrasive media rebounds at relatively low velocity as the media converts the majority of its energy into work at the surface. The sponge blast media generates approximately 80-90% less of the airborne dust levels normally experienced with conventional grit blasting media, allowing for improved safety during surface preparation.

Figure 5. Sponge-blast set-up on pipe interior

Steel surfaces, whether a pipe line or joint area within a PCCP segment, typically call for preparation to near white metal, SSPC-SP No.10 (NACE) as shown in Figure 6.

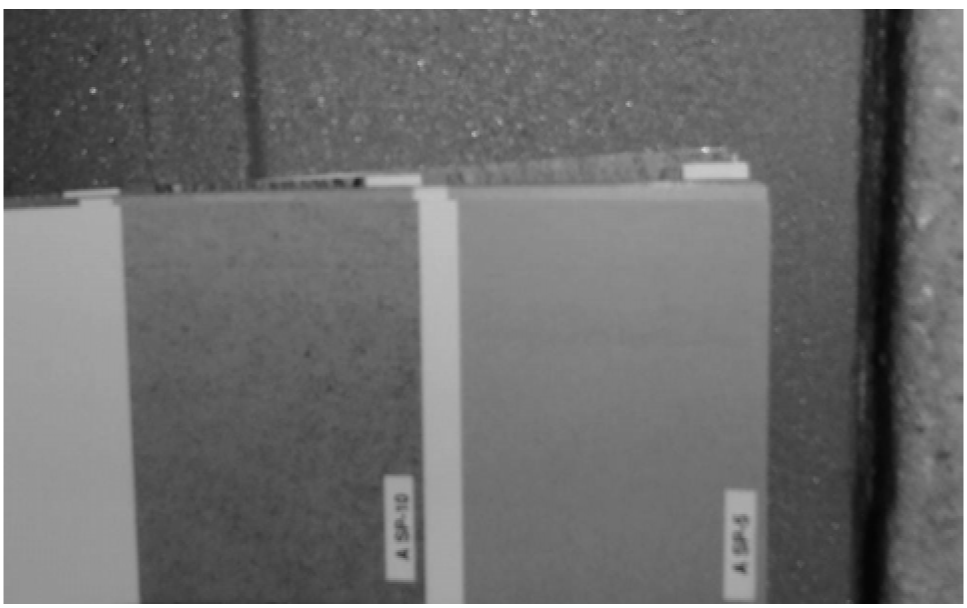

Figure 6. Surface profile cards for comparison

In the joint regions of PCCP where an FRP lining system is terminated, the inner concrete core is removed to expose the steel cylinder as shown in Figure 7. The steel surfaces at termination detail areas in the joint regions of PCCP are also prepared to a near-white metal finish, which requires abrasive blasting of the steel substrate to achieve the necessary profile.

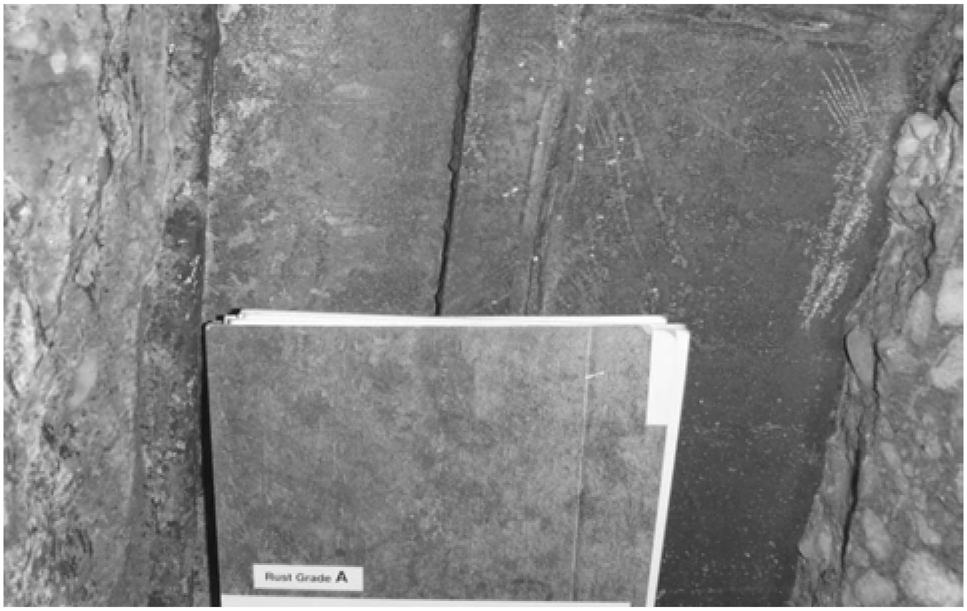

Figure 7. Joint region prior to surface preparation

Research and testing over the last several years confirmed the importance of the adequate preparation of the steel within the end termination region. Due to significant longitudinal forces applied on FRP liner, anchoring of the entire system is vital for the successful installation. Sufficient bond of the FRP liner material to the metal needs to provide adequate anchoring of the longitudinal layers to the end detail region and is necessary for ensuring leak tightness of the FRP system. Previous practices for preparation of the steel in the end termination regions for PCCP involved use of wire wheels or grinders to prepare the surface, as shown in Figure 8, left photo.

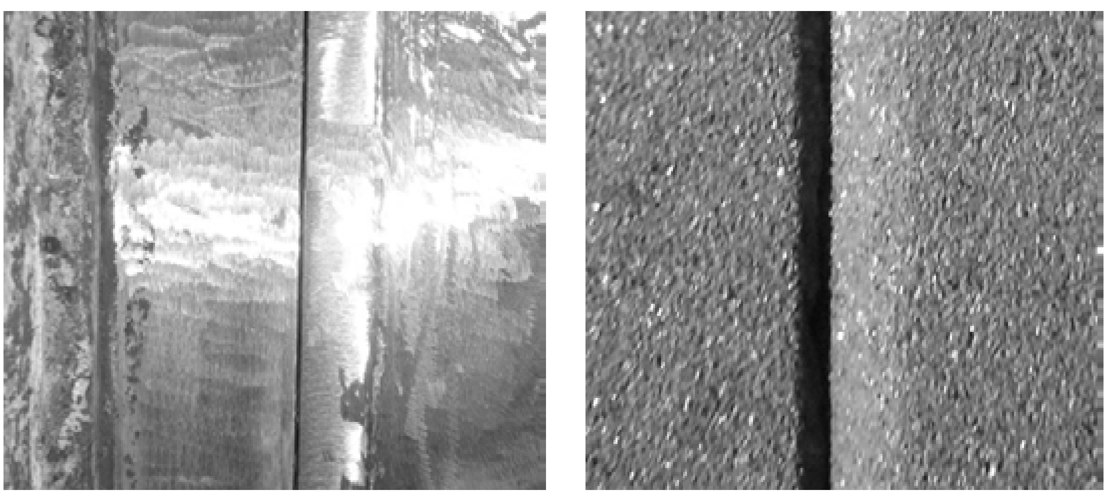

Figure 8. Close up of prepared steel substrate in joint region of PCCP with grinder (left) and sponge blasting (right)

There has been additional research done which shows that grinding steel at joints is not sufficient in achieving the necessary adhesion between the FRP lining and the steel substrate. Near white metal, SP10, as shown on the right picture for

Figure 8 has been deemed as the industry requirement, which must be achieved through abrasive blasting. If water blasting was performed surface preparation for the main regions of the concrete substrate, abrasive blasting would still be necessary for the steel regions at the end termination locations. Due to safety concerns associated with grit blasting, sponge blasting has become the more prevalent abrasive blasting process due to less dust generated during construction.

As part of the surface preparation process the soundness of the substrate is verified. Since a deviation from the specifications on any step of the process may compromise the structural integrity of the repair, Quality Assurance (QA) and Quality Control (QC) throughout the entire implementation process, including surface preparation, is a vital component of the FRP rehabilitation of pipelines. Detailed QA/QC programs have been well documented (Gipsov and Pridmore, 2012 and Gipsov, 2012) and their implementation on all FRP lining projects is critical to ensure project success.

On any construction project, discovery of unanticipated installation conditions causes challenges during construction. The key to successful projects is to anticipate challenges and to work on appropriate solutions. Therefore, among other QC tasks, installation of adhesion test panels and pull-off testing per ASTM D4541 is performed in order to confirm adequate preparation of the substrate as well as to obtain feedback regarding the condition of the existing inner core concrete. Figure 9 shows the adhesion test equipment used for the ASTM D4541 adhesion test.

Figure 9. Adhesion test equipment used for ASTM D4541 test

While specification requirements typically call for a minimum of either 200 psi or 300 psi adhesion test values, Figure 10 shows an example where a value less than the specification requirement was obtained. Following this result, the first approach would be to perform additional adhesion tests on the same test panel, because low adhesion values will be observed if the adhesion test piece (known as the test dolly) was not properly adhered to the FRP surface or if the test dolly is pulled off at a slight angle.

If test values are consistently lower than the specification requirement for a given adhesion test panel, the next step would be to repeat the surface preparation for a pipe segment and repeat the installation of an adhesion test panel and the associated tests. However, in a case where the adhesion test values are still insufficient after further surface preparation and the failure occurs within the concrete substrate as shown on the test dolly in Figure 10, this can be indicative of inadequate material properties for the inner concrete core rather than an issue with the level of surface preparation.

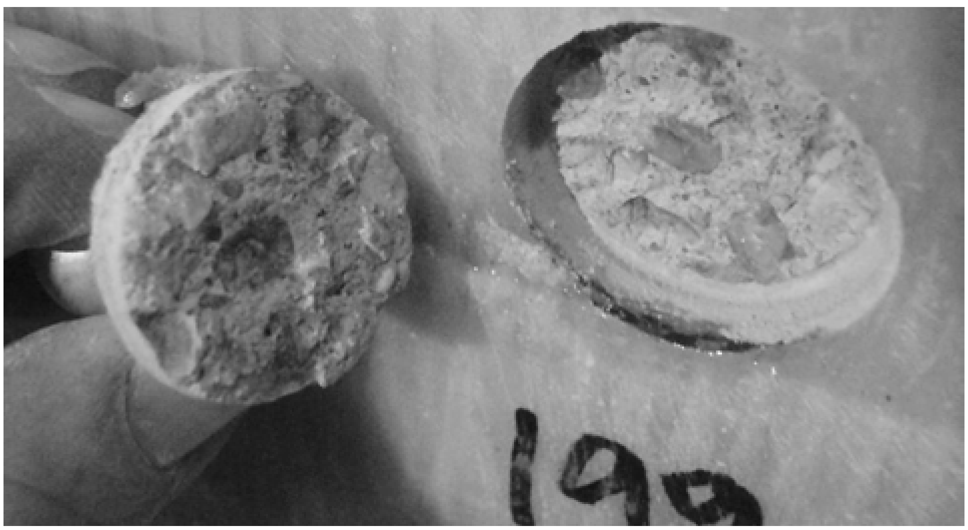

Figure 10. Adhesion test dolly used for ASTM 4541 test

Based on "as-built" specifications, the inner core concrete for selected pipelines observed by the authors was anticipated to be at least 4000 -5000 psi. However, on these pipelines the authors observed significant deterioration and testing of the in-situ concrete strength sometimes showed compressive strength of 2000 psi and lower. Since tensile strength of concrete is typically around 10% of the compressive strength of the concrete, pull-off testing of such substrate would show values of 200 psi and lower. Concrete with such low material properties do not comply with specification requirements.

Redesign of the FRP Liner

In cases where the concrete has low properties, remedial measures are required which may include modification of the design or design assumptions. One of the critical requirements for the design of FRP lining systems for rehabilitation of PCCP is a resistance to exterior loads including weight from soil cover, vehicular and rail loads, ground water pressure, and vacuum pressure as shown in Figure 11. A common practice in FRP lining design is to partially rely on the host pipe for structural integrity by taking into account the inner core concrete in conjunction with the FRP lining when resisting loads acting on the system. This design approach, known as an interactive design approach, relies on the bond between FRP liner and inner core concrete for resisting buckling under external loads. Low inner core strength values below specification requirements can require change from an FRP design with partial reliance on the host pipe (interactive design) to an FRP design with no reliance on host pipe (stand-alone design).

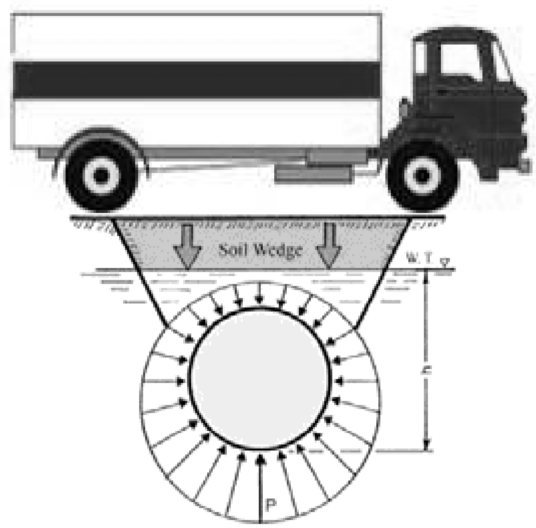

Figure 11. Diagram of external loads acting on a pipeline

During the course of redesign from the interactive to stand-alone FRP design, the number of FRP layers may need to increase to enhance buckling resistance for the stand-alone FRP liner system. While adding additional layers of FRP material can address the issue, the added time and unforeseen costs may be pose challenges for the pipeline owner.

Re-assessment of Site Conditions

Another approach to addressing the issues due to inadequate inner core concrete strength is to re-assess the original design assumptions utilized for the rehabilitated pipeline segment. Re-evaluation of the soil cover, water table and the vehicular loads on the subject pipeline may reduce design loads and confirm sufficiency of the originally selected number of FRP layers.

Checking of the assumed soil conditions, particularly the design soil modulus, E', is of particular importance. Some owners have taken into account very conservative soil moduli E' based on the previous experience of insufficient compaction of the backfill during construction. Additional soil borings along spring line of the pipe may eliminate over-conservative design assumptions for the rehabilitated pipe line. If soil modulus is still low, grout slurry or compaction to modify the modulus may be considered.

CONCLUSION

The purpose of this paper is to give the pipeline owner better control over the FRP rehabilitation process for large diameter pipelines, even if in-field conditions are different than anticipated. The first critical step is a robust QA/QC program to address issues which arise. If processes are completed in accordance to QA/QC recommendations, undesirable field conditions can be identified early on in the construction process and rectified.

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