High-Resolution Inspection of AWWA C303 Bar-Wrapped Pipe with Detailed Field Verification

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ABSTRACT

Following a high-consequence failure of a pipeline at a major freeway crossing experienced by another city in Arizona in 2022, the city of Mesa prioritized inspection of its high-consequence-of-failure AWWA C303 Bar-Wrapped Steel-Cylinder type concrete pressure pipelines (BWP) with a technology that can provide high enough resolution with actionable results. Based on the recent advances and increased track record of electromagnetic inspection, proprietary tools offered by PICA were incorporated into a visual and sounding inspection project to pilot the electromagnetic tools in about 1.7 mi of 30 in. diameter and 1 mi of 36 in. diameter BWP. The project included not only inspection of buried pipelines with unknown condition but also blind inspection of aboveground test pipes with hidden defects in the steel cylinder and reinforcing bars as well as subsequent field verification of defects that the tools identified in the buried pipelines. Field verifications included internal person-entry inspections and local external inspections in selected excavated areas as needed. This paper presents the findings from these inspections with particular emphasis on the field verification of results and discusses the effectiveness of the utilized condition assessment approach in assisting the city in its asset management program.

INTRODUCTION

While significant resources have been allocated to condition assessment of concrete pressure pipe for many years, much of that effort has focused on prestressed concrete cylinder pipe (PCCP) mainly due to typically higher pressures and higher consequences of failure with little or no warning. In the meantime, a significant amount of AWWA C303 pipe installed across the United States since the 1940s has also been degrading. These pipes are currently most referred to as bar-wrapped concrete cylinder pipe (BWP) but also referred to in older pipeline documents as Concrete Cylinder Pipe (CCP), pretensioned reinforced concrete pipe, pre-tensioned concrete cylinder pipe (sometimes confusingly so with the acronym PCCP), among other combinations of similar terminology. In all these cases, the C303 pipe is made of mild steel reinforcement wrapped on a steel cylinder under marginal tension and lined and coated with mortar to protect the steel components. These pipes were introduced in the 1940s as an alternative to steel pipe due to shortages in the supply of thicker steel plates during World War II so that part of the required amount of steel could be provided in the form of reinforcing bars (Bardakjian and Henry 2013). The resulting steel cylinder thickness used in BWP is less than that of AWWA C200 steel pipe but greater than that in typical AWWA C301 PCCP.

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With increasing awareness of degraded infrastructure as evidenced by high-consequence failures and improvements in available inspection technologies, high-resolution electromagnetic (EM) inspection technologies, which have been in demand for PCCP for many years, are now also in demand for BWP with modifications necessary to be able to detect defects in the thicker steel cylinder and reinforcing bars. However, projects with meaningful field verification of EM inspection results on BWP are still scarce.

With an approximately 155-mile-long transmission main network including a significant amount of BWP, some in high-consequence-of-failure areas, the City of Mesa (COM), Arizona, is among the utilities that demand an effective high-resolution inspection method for BWPs that can provide actionable condition information. Following a major pipeline failure experienced by another city in Arizona in 2022, COM, with contractor support from Garney and consulting support from SGH, decided to take advantage of a planned inspection project to incorporate high-resolution EM inspections within the scope to pilot the Remote Field Testing (RFT) tool provided by PICA in two 30 in. and 36 in. diameter BWP pipelines. The project was initially planned such that the effectiveness of RFT tool in detecting defects in the steel cylinder and the effectiveness of Near Field Testing (NFT) tool in detecting defects in the reinforcing bars could be evaluated; however, following pre-mobilization scans of BWP test pipes with the NFT tool, this tool was not deemed to provide additional useful data for BWP at this time, and all EM inspections were decided to be performed with the RFT tool. To develop confidence in the EM results on the buried pipelines and evaluate the accuracy and resolution of the RFT tool in detecting defects, the project also included blind verifications performed on two aboveground test pipes with various types of defects.

INSPECTION SCOPE

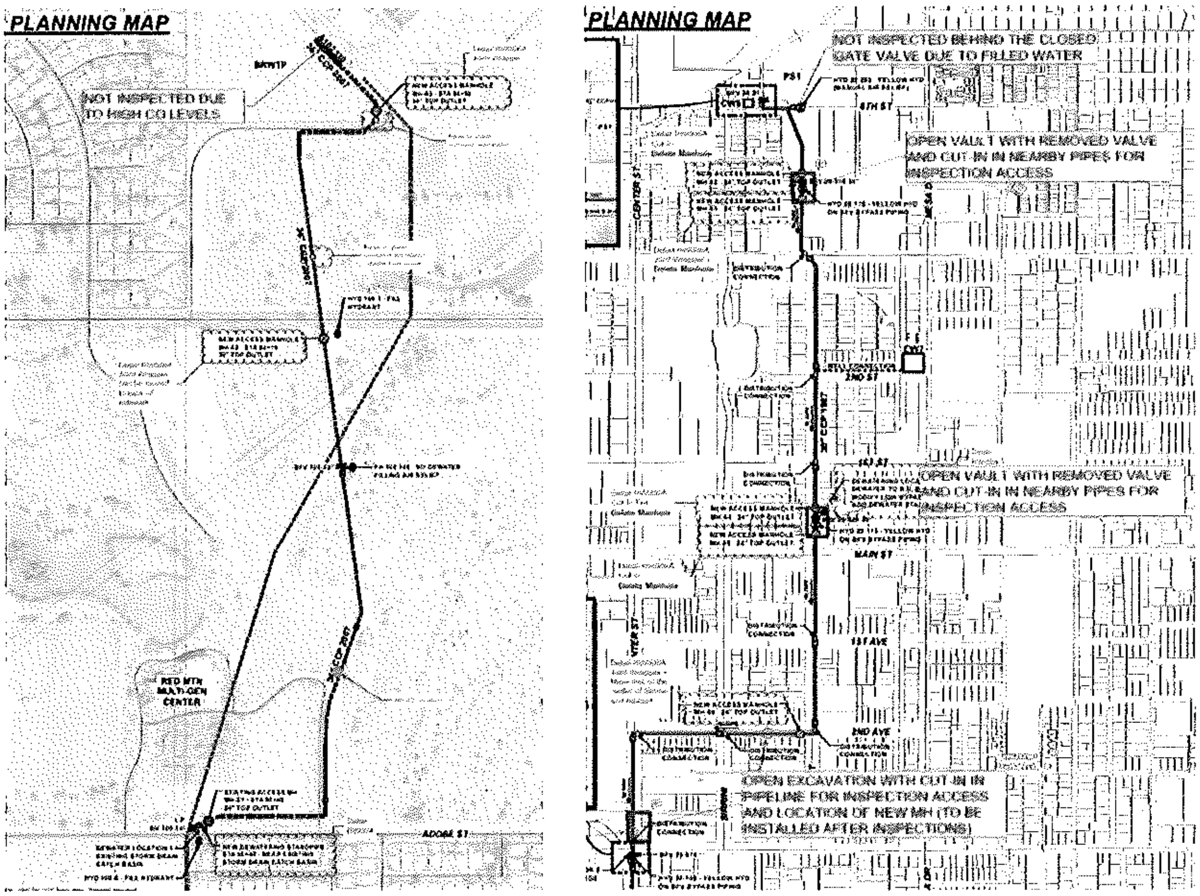
The inspection scope for this project included two separate pipeline sections referred to as Area 1 and Area 4, primarily made of 30-in. and 36-in. diameter BWP, respectively, except for a small section of 36 in. diameter BWP at the north end of Area 1 as well (Table 1).

Area 4 consists of multiple horizontal bends along the alignment, ranging from 20-deg to 90-deg angles (Figure 1a). The vertical alignment of the pipeline is generally flat, with a minor slope of up to 4% in certain sections. The pipeline in Area 4 has three access points, one near the north and south ends and one at approximately 1,600 ft from the south end. The alignment within the inspection scope also included an existing butterfly valve that was open during the inspections.

Area 1 consists of a small section of 36-in. BWP at the north end (with two horizontal bends, 10-deg and 90-deg angles) that connects to the 30-in. BWP through a tee. The 30-in. section in Area 1 consists of two 22.5-deg bends and two 90-deg bends (Figure 1b). The entire alignment of Area 1, similar to Area 4, is generally flat, with less than a 1% slope in certain sections. At the time of inspections, the inspection scope in Area 1 consisted of two access manways and three open cuts in the pipeline (two at the locations of existing butterfly valves removed for inspection access and one at the location of a new manway to be installed).

OVERVIEW OF EM INSPECTION TECHNOLOGY

To evaluate the underlying structural steel that is typically not observed with an internal visual inspection, a non-visual technique that could assess the cylinder through the internal liner was sought. PICA utilized Remote Field Testing (or RFT) in this project, using the highest possible resolution. RFT is an electromagnetic Non-Destructive Evaluation (NDE) technique that is non-contact and, therefore, unimpeded by the presence of the internal cement mortar liner. RFT works by detecting changes in an AC electromagnetic field generated by the tool. The electromagnetic field interacts with the metal in the pipe, becoming stronger in areas of metal loss. A basic RFT probe (Figure 2) consists of one exciter and one detector coil. Both coils are wound co-axially with respect to the examined pipe and are separated by a distance greater than two times the pipe diameter. The actual separation depends on the application but will always be a minimum of two pipe diameters. This separation gives RFT its name: the detector measures the electromagnetic field remote from the exciter. Although the fields have become very small at this distance from the exciter, they contain information on the full thickness of the pipe wall.



(a) Area 4: 36 in. BWP (dotted blue line) (b) Area 1: 30 in. and 36 in. BWP (solid red line)

Figure 1. Pipeline alignments in inspection scope

Table 1. Summary of inspection scope

Inspection Area	Year of Installation	Diam. (in.)	Length (mi)	Steel Cylinder Thickness (in.)	Reinforcing Bars	SGH V&S[(1)]	PICA EM[(1)]
Area 4	2007	36	0.98	0.1046 (12GA)	5/16" @ 1.11" o.c.	✓	✓
Area 1	1987	30	1.58	0.1046 (12GA)	1/4" @ 1.24" o.c.	✓	✓
	1987	36	0.08	0.1345 (10GA)	1/4" @ 1.34" o.c.	✓	✓

(1) V&S: visual and sounding inspection; EM: electromegnatic inspection.

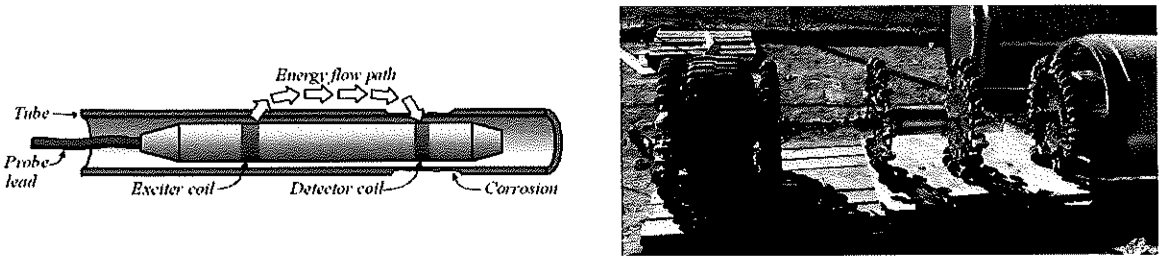


Figure 2. Basic components of an RFT probe (left) and actual tool in the field (right)

PICA's RFT tool for 36-in. pipes is modular in design, allowing individual inspection tool modules to be deflated and lowered into the 36-inch water main through access manholes. The modules are as light as possible, so they can be handled by hand if needed. Each module of the RFT tool first needs to be deflated to fit through the manholes and into the pipeline. Once inside the pipeline, the modules are re-inflated and assembled into the complete RFT tool by a 3-4 person crew. This process is reversed for tool extraction. PICA's RFT implementation for 30-inch is based on PICA's regular See Snake line of tools. This tool design assumes that there may not be any MH access locations on the water main, and as such, the tool cannot break down into smaller modules like the inflatable tool design. The 30-inch RFT tool, therefore, requires a full-bore pipe opening to be inserted.

The RFT tool for small-diameter pipes typically requires the pipeline to be drained to less than 6 in. of standing water and less than 1.5 in. of debris in place. Access locations are determined before the field work to minimize the time spent assembling and disassembling equipment while maximizing the inspection distance for each section. The length of sections that include restrictions (like a butterfly or plug valves) are purposely kept shorter to facilitate extraction of the inspection tool on the upstream side of the restriction and re-introduction of the tool on the downstream side. PICA's potable winchlines have a length of 6,000ft (~1,800m). Locations requiring traffic control are avoided when possible.

For inspections near a dead-end or open-cut access in the pipeline, the inspection scope of the tool is limited to a certain distance away from the open or dead end, usually the length of the tool.

INSPECTION PLAN

In the absence of extensive published test data on the accuracy and resolution of the RFT technology in detecting defects in BWP, an inspection plan was developed to include not only inspections and verifications in the buried BWPs in Areas 1 and 4 but also "blind verifications" in two test pipes to evaluate the tool's capabilities and potential limitations. As part of the plan, PICA first inspected a 36-in. test pipe with hidden defects induced by SGH and then inspected the 36-in. diameter BWPs in Areas 4 and 1. After reporting the results from the 36-in. test pipe, PICA continued with the 30-in. diameter buried BWP in Area 1, then finished with the inspections on a 30-in. test pipe.

BLIND VERIFICATIONS IN ABOVEGROUND TEST PIPES

The primary purpose of the blind verifications was to evaluate the types and extents of defects detectable by the RFT tool, thereby developing confidence in the results of inspections performed in Areas 1 and 4 while also providing quantitative results that can be used in consideration of the RFT tool for COM's future BWP inspection projects.

Test Pipe Properties

The test pipes were purchased based on the diameter requirements (30-in. and 36-in.) and availability without any information on the pipe properties. During preparation of the defects in the test pipes, the following pipe properties were measured:

Table 2. Summary of test pipe properties

Pipe Size	Cylinder thickness	Bar diameter	Bar spacing	Mortar coating thickness
36-in.	0.1644 in. (8GA)	5/16 in.	1.78 in. o.c.	0.91 in.
30-in.	0.1046 in. (12GA)	1/4 in.	0.70 in. o.c.	0.75 in.

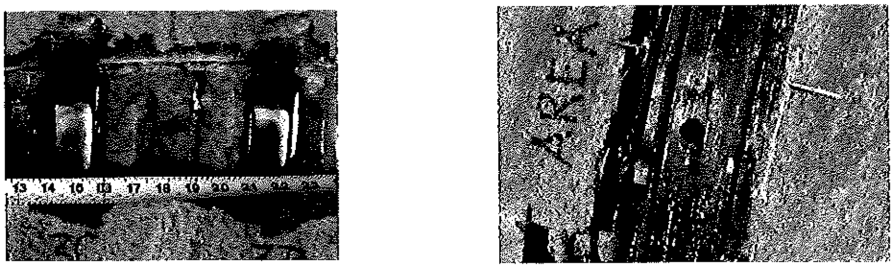
Verification Process

Several hidden defects were introduced into the test pipes, as summarized in Tables 3 and 4, for PICA to detect. The mortar lining or coating (as applicable) was restored after inducing the defects, and the pipes were covered with a tarp before the EM inspections. The test pipes were scanned with RFT using multiple frequencies, and the preliminary results were tabulated. SGH compared the preliminary results to the documented induced defects and provided PICA with factual information on one of the induced defects for use in further calibration if needed. PICA adjusted the calibration slightly, which resulted in increased section loss values and no changes to the locations.

Induced Defects vs. EM Results in 36 in. Diameter Test Pipe

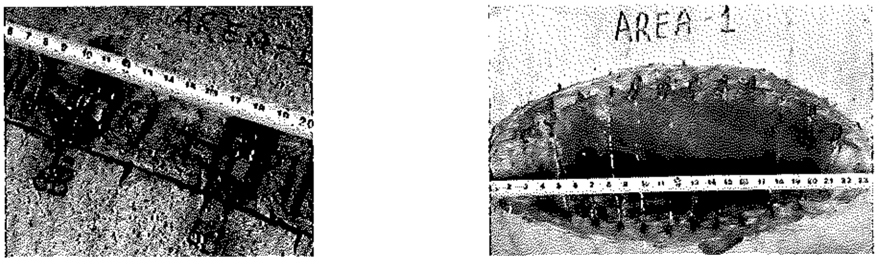
Most of the induced defects included localized section loss or through holes in the steel cylinder with varying sizes, spacings, and extents of loss, which were prepared by grinding, drilling, or cutting. In many cases, this involved locally removing reinforcing bars to provide access to the steel cylinder. In addition to studying the defects in the steel cylinder, one area was prepared by removing a significant amount of bars without damaging the steel cylinder to study the potential effect of such a condition on the RFT signals, although RFT is not intended to see behind the thick steel cylinders in BWP. The section losses were measured using an ultrasonic thickness (UT) gauge, and through-holes were measured with a digital caliper. All defects were documented by distance from the pipe end (offset) and clock position. Typical views of induced defects are shown in Figure 3, and a general comparison of the induced defects and EM results are presented in Table 3 for the 36-in. test pipe.

In addition to intentionally induced defects, EM inspection also identified an area of "wall gain" and three areas of "magnetic anomaly." Upon making openings in the mortar coating, the wall gain was found to be an area with several spliced reinforcing bars, and areas of magnetic anomalies did not have significant visible distress, as expected by PICA.



(a) Section-loss defect in the steel cylinder

(b) Through-hole defect prepared by drilling



(c) Through-hole defect prepared by cutting

(d) Area of removed bars, no damage to the steel cylinder

Figure 3. Typical views of defects induced in 36 in. test pipe

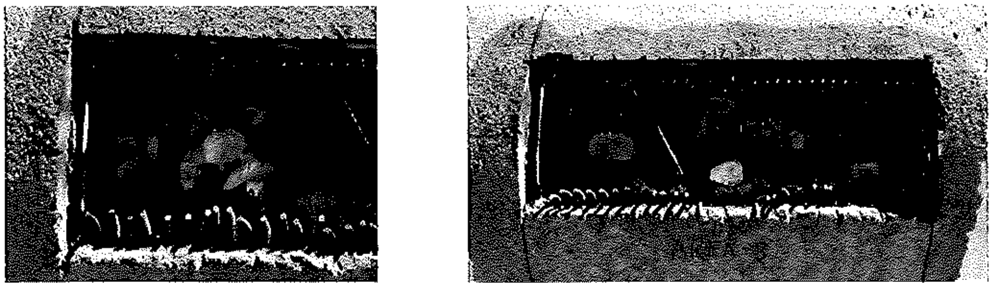
Table 3. Summary of induced defects and EM results in 36-in. test pipe

Area	Type(1)	Clock	Defect Size	Actual % Loss	EM Results				
					Longit. Offsets	Circum. Offsets	# of Defects	Length	Wall % Loss
1	RB	3:00	Oval 24”x12”	0	Not Observed by PICA				
2	3 SL	1:00	2.1 – 3.2 in^2	32 – 76	±1”	±15-deg.	3	2.1” – 2.6”	57 – 71
3	3 SL	2:00	2.7 – 3.2 in^2	75 – 81	±1”	±15-deg.	3	2.1” – 2.5”	73 – 75
	1 RTH		2.9 in^2	100	±1.5”	±15-deg.	1	2.4	80+
4	3 SL	1:00	9.0 – 9.9 in^2	17 – 71	±3”	±15-deg.	3	2.8” – 3.8”	51 – 75
5	1 SL	6:00	10.5 in^2	79	±1.5”	±15-deg.	1	2.3	65
6	5 RTH	11:00	2.9 – 4.2 in^2	100	±3”	±30-deg.	5	1.7” – 3.1”	80+
7	4 CTH	9:00	1/8”ø – 3/4”ø	100	±3.5”	±15-deg.	1 (largest)	1.7”	80+

(1) RB: Removed Bars; SL: Section Loss; RTH: Rectangular Through-Hole; CTH: Circular Through-Hole.

Induced Defects vs. EM Results in 30 in. Diameter Test Pipe

SGH induced similar defects in the 30-in. section as in the 36-in. section using the same process, with the intention of refining and confirming the accuracy and resolution of detection. In addition, a specific attempt was made to study the detectability of various section-loss defects occurring in a given area with variable spacings: multiple closely spaced defects in one area (Figure 4a) and multiple relatively more spaced defects in another area (Figure 4b). These areas were intended to reflect conditions observed during the visual and sounding (V&S) inspections performed in parallel in the buried pipelines in Areas 1 and 4. A general comparison of the induced defects and EM results are presented in Table 4 for the 30-in. test pipe. A detailed discussion of induced versus detected defects, including results of ongoing evaluations, will be presented in the future.



(a) Multiple closely-spaced defects

(b) Multiple relatively more spaced defects

Figure 4. Typical views of defects induced in the steel cylinder in 30 in. test pipe

Table 4. Summary of induced defects in 30-in. test pipe

Area	Type(1)	Clock	Defect Size	Actual % Loss	EM Results				
					Longit. Offsets	**Circum. Offsets**	**# of Defects**	**Length**	**Wall % Loss**
8	6 SL	1:00	0.9 – 3.8 in^2	55 – 86	NA(2)				
9	6 SL	1:00	0.6 – 2.5 in^2	28 – 75					
	2 CTH	1:00	~1/2”ø	100	±1.5”	±30-deg.	1	7.9”	NA
10	3 CTH	9:30 - 11:00	3/8”ø – 1/2”ø	100	±0.5”	±30-deg.	2	2.0” – 3.7”	46 – 80+

(1) SL: Section Loss; CTH: Circular Through-Hole.

(2) These defects could not be characterized due to unusual undulating baseline in the RFT signal in this portion of the test pipe, which requires further investigation.

INSPECTION OF BURIED BWP

In each pipeline, inspections included initial V&S inspections by SGH, EM inspections by PICA, follow-up local internal inspections including ultrasonic thickness (UT) measurements in selected areas, evaluation of results to determine the need for excavation, and external inspections at selected excavation sites. The following sections only present observations relevant to this paper.

Inspections of 36 in. BWP in Area 4

Visual and Sounding Inspections: These inspections were performed at the start of the project. The presence of ¼” to ½” thick alum deposits on the pipe wall obscured direct visual observations to a certain extent. No anomalies were observed in the pipe barrels throughout the pipeline, except for the outlines of typical cracking in the mortar lining visible through the deposits.

EM Inspections: These inspections were completed over 3 days, including troubleshooting challenges presented by the alum deposits and the presence of multiple bends (and a butterfly valve) between access points. PICA's findings in this area were limited to six observations: one pipe with an 84-in. long area reported as "mechanical stress" and three pipes with a total of five areas of 20 to 40% section loss in the steel cylinder with low confidence.

Follow-Up Internal Inspections: SGH revisited the PICA-identified anomaly locations inside the pipeline to verify the results.

- At the mechanical stress anomaly, the pipe had an existing repair patch in the mortar lining. Upon removal of the patch, the steel cylinder was found to have a spiral joint and a local minor bulge (about 4"x3") that was debonded from the exterior coating. UT measurements at the location did not reveal any section loss.
- At one of the low-confidence section loss anomalies, mortar lining was removed in a 6"x6" area to observe the steel cylinder. No visual anomalies or section loss were identified, consistent with PICA's low confidence.

Inspections of 30 in. BWP in Area 1

In the short 36 in. diameter section of Area 1, neither the V&S inspections nor EM inspections identified any anomalies. The observations in Area 1 that required verification and evaluation were in the 30-in. diameter segments, as presented below.

Visual and Sounding Inspections: SGH inspections in this pipeline revealed four pipes, each with an area of spalled mortar lining ranging in size from 25 sq. in. to 90 sq. in. near the crown of the pipes, bringing into question a potential external impact to the pipes at some point in the past (Figure 5). Three spalls were away from pipe joints, where the steel cylinder was exposed, corroded, and bulged at two locations. One spall was at a pipe joint, where only the joint ring was exposed and corroded. UT measurements on exposed steel surfaces indicated up to 50% section loss in the steel cylinder of one of the pipes and no measurable loss in the other pipes.

Figure 5. Areas of spalled mortar lining and exposed/corroded steel cylinders

EM Inspections: PICA inspected this pipeline over 3 days and reported the following:

- Of the four pipes with spalled mortar lining identified by visual inspections, one pipe was detected with an 11-in. long 37% section loss in the steel cylinder with low-to-medium confidence, which matched the pipe with up to 50% steel loss measured by SGH.
- In two other pipes with spalled mortar lining away from joints, initial analysis of EM data did not indicate any defects; however, upon comparison with internal visual inspection results and reanalysis, EM results were updated to include these two pipes with "low-confidence, small-amplitude" defects with 77% and 80%+ section loss, which could be

indicative of small but deeper section losses that were not observed visually on the inside. Given low confidence, it is also possible these two defects do not exist.

- One pipe not identified as distressed by V&S was detected to have two areas, 2 in. and 4 in. long, estimated with 70% section loss.
- Six pipes, each with one area of mechanical stress, ranging from 25 to 120 in. long.

Follow-Up Internal Inspections: SGH revisited the pipes to verify the EM results, with particular attention to pipes that did not have specific observations from V&S inspections:

- In the pipe with two areas of estimated 70% section loss, SGH located an existing mortar patch, removal of which revealed a corroded and bulged steel cylinder with two through-holes (<1/4"ø) adjacent to a lap-weld in the cylinder and up to 50% section loss in the vicinity of the through holes (Figure 6). This is a major observation because these defects could have gone unnoticed without detection by EM.
- In the six pipes reported with mechanical stress, 6 in.x6in. windows made in the mortar lining revealed a lap-weld joint in the steel cylinder in three pipes and no other visual anomalies or section losses.

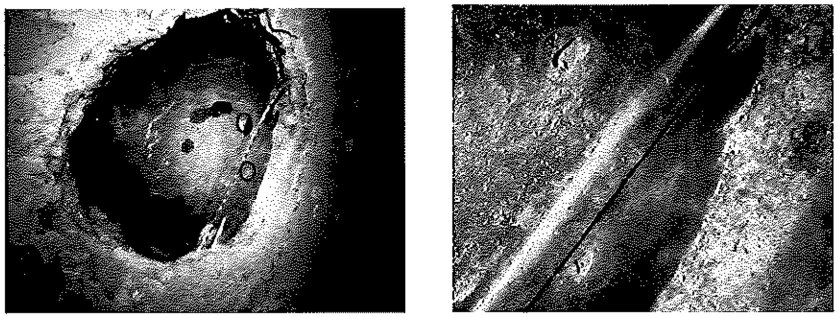


Figure 6. Pipe with two through holes in the steel cylinder detected by EM and not by V&S (red dotted line: spiral weld in cylinder, blue circles: through holes)

Local External Inspections: Based on a combined evaluation of results from the internal V&S and EM inspections, local external inspections were deemed necessary at five pipe locations either via local excavation or potholing as allowed by local field conditions:

- Four pipes with spalled mortar lining on the inside to investigate the potential external impact and the current external condition of the pipes (three pipes shown in Figure 5 and one pipe with spalling near a joint). Of these four pipes,
    - One pipe with section loss in the cylinder identified by both internal V&S and EM inspections was found to have an existing previous repair in the mortar coating on the outside. Upon removing the mortar coating in this area, a depression in the steel cylinder and several broken bars were found (Figure 7a).
    - One pipe with spalled mortar lining but no measured section loss during internal inspections was found to have local damage under the mortar coating with the local wires bent radially inwards (Figure 7b).
    - One pipe with spalled mortar lining but no measured section loss during internal inspections was found to have no visible damage on the mortar coating (Figure 7c).
    - One pipe with spalled mortar lining near a joint and limited section loss in the joint ring identified during internal inspections had no visible damage around the joint on the outside (Figure 7d).

- One pipe with two through holes identified by EM and not by V&S (internal condition previously shown in Figure 6) had damaged mortar coating, with multiple broken bars (blue arrows in Figure 7e), thinning bars (yellow arrows), and a depression in the steel cylinder with through holes (green circles for holes identified internally; red circle for a new uncovered hole).

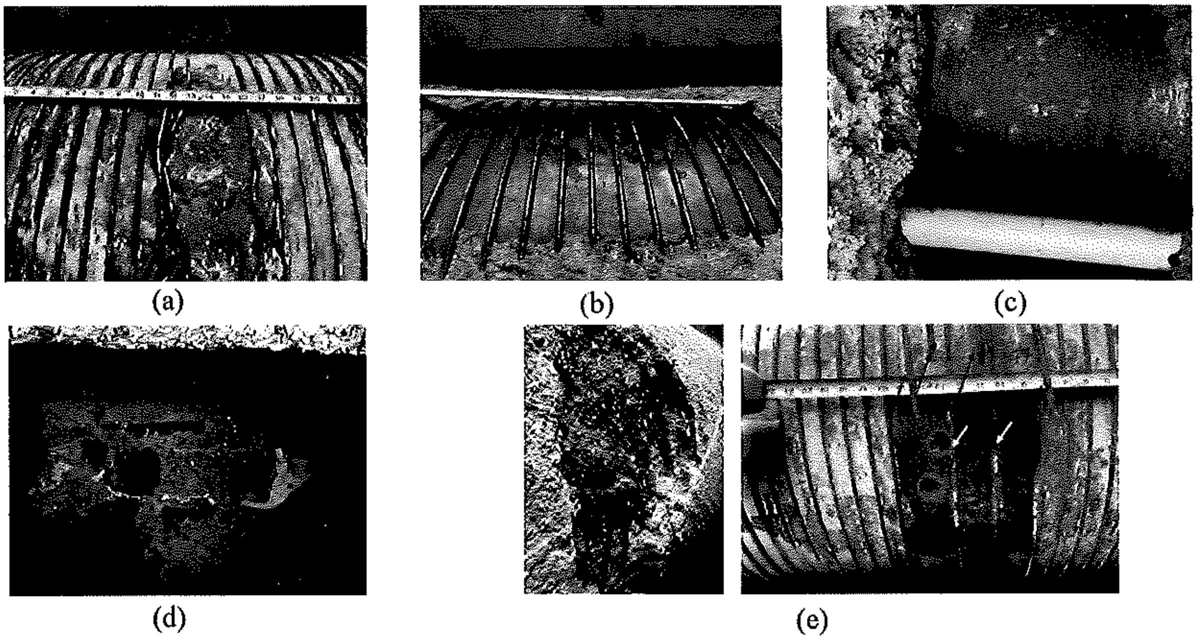

(a) (b) (c) (d) (e)

Figure 7. External condition of pipes identified with defects via internal inspections

CONCLUSIONS

A combination of visual and sounding inspections and the EM RFT tool proved effective in identifying defects that one method alone could not identify. Despite some operational challenges in this project due to significant accumulation of alum in the pipelines and presence of bends, and other features that affected the efficiency of the EM inspections to some extent, the RFT tool provided value in identifying both thinning and through hole defects in the steel cylinder with acceptable longitudinal and circumferential location accuracy beyond a certain threshold of defect detection, such as a diameter threshold between ½ in. and ¾ in. for through holes in the steel cylinder. Based on the blind verifications on test pipes performed with the RFT tool presented herein and the pre-mobilization trial scans with the NFT tool (not presented here), it appears that until the development of inspection tools that can reliably detect defects in the reinforcing bars behind the relatively thick steel cylinder of BWP, non-destructive condition assessment of BWP may be limited to assessing the condition of the steel cylinder only, using RFT. Additional research and development and experience from similar projects emphasizing field verification of EM results may lead to improvements that could benefit all BWP stakeholders. In addition, the efficiency of the EM inspections can likely be improved by pre-cleaning the pipeline interior to remove significant surface deposits and utilizing additional access points to avoid multiple bends in a given inspection section.

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