Discussion of "Pipe Efficiency Analysis at a Water Utility" by Amarjit Singh and Stacy Adachi

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The driving message behind the authors' paper is that concrete cylinder pipe (CC is the abbreviation they used) is not as efficient, i.e., cost-effective, as the primary alternate water-pipe materials [cast iron, (CI), ductile iron, (DI), or PVC] used by the Honolulu Board of Water Supply (BWS). The discussers feel that the authors' paper contains errors that affect the conclusions. The authors' paper reports significantly variant material performance than experienced in the rest of the United States.

Terminology

The discussers feel that one error in the original paper is in terms of the inexact terminology used by the concrete cylinder pipe manufacturer and BWS employees. This error is that most of the breaks reported as concrete cylinder pipe were actually on mortar-lined and coated steel pipe. It has been reported (Wakayama, interoffice correspondence, Ameron Hawaii 2011) by employees of Ameron Hawaii that neither the employees of the BWS nor those of the pipe manufacturer commonly distinguish between the two types of pipe in conversation or reports. The authors did not distinguish between the performance of mortar-coated welded steel pipe (WSP) and concrete cylinder pipe (CCP). Concrete cylinder pipe, manufactured in conformance with the standard American Water Works Association (AWWA) C303 (AWWA 2003), was not supplied to the BWS until the mid-1970s. All pipe reported in the authors' paper to be concrete cylinder pipe that was manufactured from the 1940s through approximately 1975 was mortar-lined and coated steel pipe. Given that the mean time to first failure for all mortar-coated pipe, including both the WSP and CCP, was more than 28 years, perhaps there have been only one or two breaks in the concrete cylinder pipe. Concrete cylinder pipe has significantly better corrosion resistance performance when compared with mortar-coated steel pipe, so the intermingling of the performance history of the two products likely underestimates the performance of concrete cylinder pipe.

Pipe Cost

The authors directly compare the cost of the concrete cylinder pipe (CC, but including both the WSP and CCP), with an average diameter of almost 30, to other types of pipe with an average diameter roughly one-third of the average diameter of the pipe identified as CC. The use of that abbreviation in this discussion will indicate the combination of WSP and CCP, as was done by the authors. The authors do not acknowledge that larger pipes are more expensive to purchase and fix. Additionally, the authors report their data in a manner that generates a report of a greatly increased average repair cost per break of CC relative to the other types of pipe reviewed. The authors do not report the fact that if a pipe that is 3× larger in diameter breaks, the amount of water to be pumped out of an equal length is 9× greater; hence, breaks on a larger pipe will typically require more time to fix because water removal is a much bigger operation. A larger pipe also has more mass per meter (foot) to repair and is in a larger trench, which results in larger equipment being required to perform a repair and more cost to excavate and rebed the pipe.

To present some specifics regarding the manner in which the authors report their data, readers should review Table 2 in the authors' paper. The authors' Table 2 presents the installation cost per linear meter (foot) for CC pipe for each year from 1988–2002, and then utilizes an inflation rate to list the installation cost per meter (foot) for CC pipe in constant 2009 dollars. The adjusted costs range from US$231.27 in 1990 to US$1,419.10 in 1995, plus one statistical outlier of US$3,434.98 in 2002. Rather than discard the high and low values and average the rest, or provide additional investigations regarding the remarkably high cost in 2002, the authors averaged the cost for all the years as if they all had equal weight. By including the extraordinary 2002 cost, the average installation cost for CC rose from US$670.56/LF for years 1988–2001 to US$854.86/LF for years 1988–2002. This data selection increased the reported cost of CC installation by more than 27%.

However, the authors appear to have provided a sufficient amount of information for a more accurate installation cost to be calculated. The authors' Table 3 presents the length of each type of pipe in the BWS system for years 1988–2008. It is unclear whether the length reported is at the beginning or end of the reporting year, but for purposes of illustration the discussers will assume that the lengths reported represent the lengths at the beginning of each year. With that assumption, and the report that in 1988 there were 114.7 mi of CC in the BWS system, and in 1989 there were 116.8 miles of CC in the BWS system, then the difference between these two numbers, 2.1 miles, represents the amount of CC installed in 1988. If the discussers take that information, multiply each year's length installed by each year's reported installation cost, sum those products, and divide by the total length installed from 1988–2002, the discussers calculate the weighted average of the replacement cost of CC pipe, i.e., US$565.60/LF (Table 1).

There are two years, between 1996 and 1997, and between 2001 and 2002, when the length of CC in the BWS system reportedly reduced. It is unclear how an installation cost per meter (foot) could be reported if CC pipe was actually removed unless it was replaced with another type of pipe. This aspect of the discussers' analysis requires more information than is available from the original article. For those years and the purposes of this segment of the discussion, the discussers have multiplied the 2009 installation cost per meter (foot) by zero instead of by a negative number. One of those 2 years of reported decrease in the length of CC pipe in the BWS system also had the third highest replacement cost, so the discussers' analysis will cause the average installation cost to decrease somewhat disproportionately. Even so, the discussers contend that their weighting of costs is more appropriate than including in the average a perhaps excessive value of US$3,434.98/LF for year 2002 on a minimal installed length of pipe.

Table 1. I$/LF for CC Pipes in 2009 Constant Dollars for Fiscal Year 1988–2002

FY (year)	Miles installed in year	Miles installed in year, no negative lengths	I$/LF ($)	Inflation rate per FY from year to 2009 (f%)	I$/LF (2009 constant US$)	Column 3 × column 6
1988	2.1	2.1	388.00	2.292	624.46	1,311.37
1989	2.1	2.1	214.09	2.261	334.81	703.10
1990	8.9	8.9	152.08	2.231	231.28	2,058.41
1991	1.4	1.4	323.32	2.202	478.52	669.93
1992	1.5	1.5	308.05	2.174	444.03	666.04
1993	3.3	3.3	192.83	2.147	270.88	893.92
1994	1	1	638.41	2.121	874.63	874.63
1995	1.1	1.1	1,061.48	2.096	1,419.17	1,561.09
1996	−0.7	0	114.12	2.071	148.97	0.00
1997	1.3	1.3	684.91	2.047	873.45	1,135.48
1998	2.6	2.6	715.15	2.024	891.50	2,317.91
1999	0.1	0.1	483.14	2.002	589.06	58.91
2000	1.8	1.8	791.14	1.98	943.82	1,698.87
2001	−1.5	0	1,081.61	1.959	1,263.21	0.00
2002	0.5	0.5	3,002.93	1.939	3,435.01	1,717.50
Column totals		27.7				15,667.16
Actual average I$/LF for CC pipes for years 1988–2002						565.60

Note: FY = fiscal year; I$ = installation cost; LF = inflation rate adjustment coefficient. Adapted from the original article.

The take-away message from this aspect of the discussion is that when the redefined installation cost per meter (foot) of US$565.60 for CC pipe is compared with the installation cost per meter (foot) of US$222.03 for CI and DI, and US$219.78 for PVC, it is clear the BWS got a bargain with CC pipe. The CC pipe averages approximately 3× larger in diameter, or 9× greater in flow capacity, for an installation cost of only 2.6× greater.

The authors decided to set the installation cost of CI to be the same as the installation cost of DI in their analysis. The discussers note the drastic reductions in cylinder thickness from CI to DI pipe designs. The iron pipe industry moved to ductile iron thickness designs in large part to reduce the cost of materials in CI pipes. It is incorrect to assume that CI installation costs are as low as those of DI.

Another area of data reporting that the discussers feel is in error is presented in the authors' Table 4, which presents the "Average Repair Cost per Break per Length in Ground and Reciprocal." The authors propose that "A high (repair cost/break/length in ground) signifies how badly the pipe type is performing compared to other pipe types in the system." The discussers question how the amount of pipe in the ground is a valid metric for a cost per break analysis. A more applicable question is whether the cost per break is reasonable for each type of pipe. In this instance, if one multiplies the repair cost per break per length in ground presented in the authors' Table 4 by the length of each type of pipe reported in the authors' Table 3, this discussion (Table 2) reports the repair cost per break for each type as a supplement for the authors' Table 4.

Considering that the average size of the CI, DI, and PVC was all around 10, and that the average size of the CC was around 30, the PVC repair costs appear high, but the CC pipe costs appear proportionate.

Table 2. Average Repair Cost per Break per LIG and Reciprocal

Pipe type	R$/B/LIG	1/(R$/B/LIG) × 100	Actual average repair cost/break (US$)
CI	5.27	18.98	5,148
DI	12.19	8.20	5,751
PVC	39.64	2.52	11,004
CC	119.50	0.84	17,256

Note: Adapted from the original article. R$/B/LIG = repair cost per break per length in ground.

In regard to reliability, the authors propose Eq. (4) in the original paper. However, the authors introduce the formula with a caveat that the discussers feel is in error, i.e., "When the failure rate is constant . . . " The authors subsequently present that the mean time to first failure of a CC pipe was 28.2 years, second-best only to the much thicker wall CI pipe. If the CC pipe failed at a constant rate of one every 28.2 years, there would only be a handful of CC failures because the mortar-lined and coated steel pipe was first introduced in the 1940s. The discussers feel that Eq. (4) in the original paper is not applicable, and if so the subsequent reliability analysis in the remainder of the authors' paper is not valid.

The results of the authors' data envelopment analysis presented in Tables 11 and 14 may also be in error. The authors do not acknowledge the cost differential of CC pipe that is typically 3× the diameter of the other types of pipe. All analyses by the authors that include consideration of the time to make a repair do not report the fact that it takes 9× more time to empty a pipeline that is 3× larger in diameter. The authors also do not report the other previously noted increased repair costs for large pipes, which are independent of the pipes' material composition. The discussers feel that the authors' contention that CC pipe is more inefficient is incorrect. As presented in this discussion (Table 2), the discussers feel that the authors' contention that "the repair cost of CC pipes was almost 23 times more than that of CI pipes" is not supported by data. By the authors' own data, the repair cost per CC break is about 3.4× the cost of a CI break, and almost exactly 3× the cost of a DI break, which can be expected for a pipe type averaging 3× the diameter of the CI and DI pipes in the system.

Repair Procedures

The authors state that BWS field personnel "would prefer not to install more CC pipes as they are more difficult to repair than pipes of other materials." The discussers assume the greater difficulty of repair procedure is as follows: (1) the mortar coating must be removed; (2) the pipe manufacturer has traditionally recommended welded repairs on thin cylinder steel, which for less-skilled welders can be difficult; and (3) the welded repairs often require repair of the mortar lining. The BWS should note that there are repair procedures for CC pipes that utilize clamps instead of welding. This process consists of removing the mortar coating around the hole in the cylinder, cutting a thick rubber seal to fit around the cylinder hole and within the removed mortar coating, and then sealing the rubber against the cylinder with a clamp. The clamp is then encased in cement mortar. This repair process requires less excavation to provide welder access and no access to the pipe interior. Details of the repair processes have been and are available from Ameron's Water Transmission Group.

Corrosion and Corrosion Control

The authors do not report that various piping materials can be cost-effectively designed for much longer-lived performance by implementing simple corrosion-control mechanisms. Such mechanisms have already been in use on DI pipes in the BWS system (Richards et al. 1990).

Particularly on older pipelines, a contributing cause of failure of CI, DI, and CC pipes is often corrosion of the metal cylinder. Metallic corrosion occurs at anodic sites on a metallic pipe cylinder. Most corrosion processes on buried pipelines require an electrolyte (moist soil), oxygen access to the metal, and a difference in the electrical potentials of various areas of the pipe cylinder surface.

To prevent metallic pipe cylinder electrochemical corrosion, oxygen must be kept from the pipe cylinder or the current in the electrolyte must be disrupted or redirected away from the pipe.

Mortar coating of pipe causes a chemical change on a pipe's steel cylinder surface that disrupts a potentially corrosive electric current (Hausmann 1967). Portland cement mortar has a high pH of at least 12.5. If this high pH is maintained on a steel surface, an iron oxide that resists the low-voltage, corrosion-causing electric current flow forms on the steel. This corrosion protection can be demonstrated by immersing steel nails in jars of water, wherein one jar has portland cement mortar blocks in the water and one does not. The nails in the jar with the mortar blocks will be passivated by the high pH in the water but the nails in the other jar will rust.

Mortar also slows the diffusion of oxygen to the steel surface, but the efficacy of this effect depends on the porosity and moisture content of the hardened mortar and whether the mortar is in close contact with the steel surface.

The corrosion-resisting effectiveness from maintaining close contact between the mortar coating and pipe steel has been demonstrated by testing (Chi and Hausmann 1966). American Pipe and Construction (now Ameron International Corporation) performed salt spray testing on two pieces of mortar-coated steel pipe and one piece of concrete cylinder pipe in the style of AWWA C303 (AWWA 2003). The electrical potential of the pipes' surfaces was measured relative to the potential of a copper-copper sulfate electrode. When such potentials are more negative than −300 mV, corrosion of steel is indicated. The ordinary mortar-coated steel pipe almost immediately showed corrosion potentials, whereas the concrete cylinder pipe with its bar-wrap-reinforced coating continued to resist corrosion with respect to the 29-month duration of the test (Fig. 1).

The difference in the corrosion-resisting performance of the mortar coating on ordinary steel pipe versus the concrete cylinder pipe is that the bar wrap holds the mortar in close contact with the steel cylinder surface. Ordinary steel pipe mortar coatings are typically reinforced with wire in the middle third of the thickness of the mortar. This reinforcement holds the mortar on the pipe but cannot prevent the mortar from delaminating from the steel pipe surface. The distance of separation of the mortar from the steel is small but more than sufficient for oxygen availability and loss of pH passivation when the mortar coating dries. Cyclical wetting and drying will cause negatively charged chloride ions to migrate to anodic points on the steel pipe surface and over time corrosion will accelerate.

This same process will eventually also happen on concrete cylinder pipe if the pipe is cyclically wetted and dried, but the action of the bar holding the coating in close contact with the steel will greatly extend the time to corrosion initiation.

If a mortar coating remains moist the rate of oxygen diffusion stays very low and the time to corrosion can be extended nearly indefinitely. Moisture also allows the high pH of the mortar to be transferred to the steel surface even if the coating is delaminated. It is these characteristics that allow regular mortar-coated steel pipe and AWWA C303 (AWWA 2003) pipe to perform extremely well in low-resistivity clays without supplemental corrosion protection.

Some of the CC pipes in the BWS system are installed in an environment in which the pipe cylinder surface is no longer protected by the high pH of the mortar coating. Simple, cost-effective application of an appropriate design for corrosion resistance will allow the CC pipe or any other metallic pipe used by BWS to provide a nearly indefinite performance life. The discussers feel

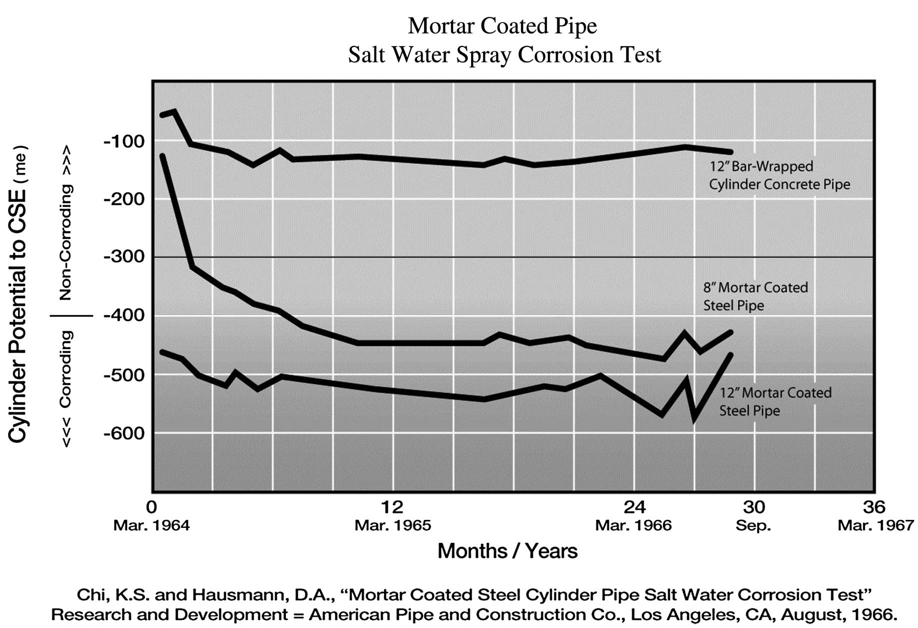

Fig. 1. Mortar-coated pipe, saltwater spray corrosion test (reprinted with permission from Ameron International Corportation)

that the authors did not fully consider the effect of such an approach on pipe efficiency.

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