Causes of Etiwanda Pipeline Lining Failure

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Typical Mortar Lining Failure Inside Etiwanda Pipeline.

Abstract: Staff from the Metropolitan Water District visually inspected 5.3 miles of the 144 inch diameter Etiwanda Pipeline to evaluate the condition of the internal mortar lining. The inspection showed that large portions of the lining are either failing or have failed. Approximately 35% of the total length of the pipeline has either missing or delaminated mortar. This constitutes a significant failure. The pipeline's structural integrity is at risk due to corrosion if the lining is not replaced or repaired.
There are several factors that contribute to the lining failure. The most significant factors are:

1. The pipe was designed for a higher stress than historically recommended by AWWA standards or traditionally used by MWD. The higher allowable stresses will cause the

liner to crack more and have larger cracks than on typical mortar lined welded steel pipelines.

2. The Etiwanda Pipeline functions as a penstock for the Etiwanda Power Plant. Pressure fluctuations caused by the Etiwanda Power Plant are preventing the cracks from autogenous healing. The Etiwanda Power Plant peaking characteristics cause pressure fluctuation of approximately 40 psi per day. These pressure changes are damaging the lining because it prevents the mortar lining from autogenous healing (a natural process by which cracks are filled with calcium carbonate and knit the mortar back together when put in contact with water). The inability of the lining to heal is causing the lining to delaminate from the steel pipe wall. This eventually causes the lining to fail due to the effects of gravity.

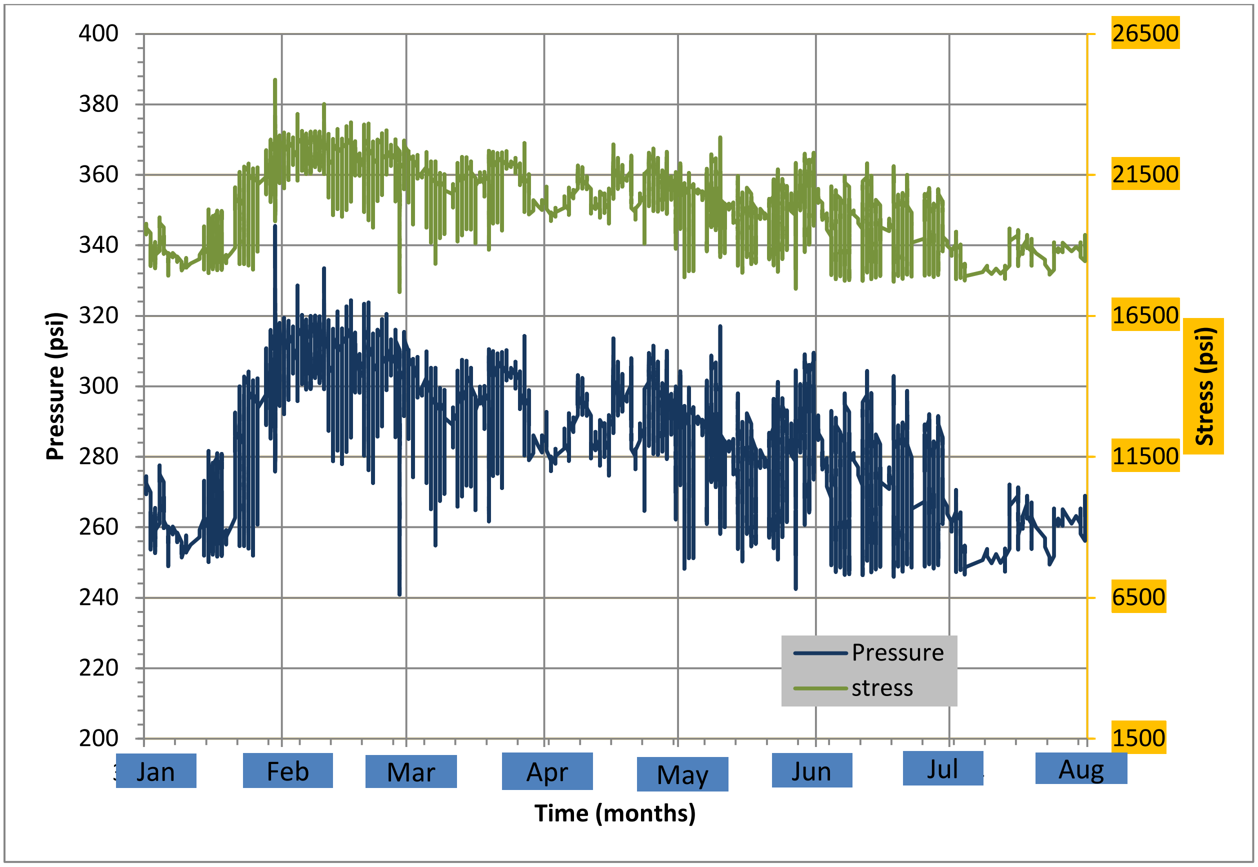
In view of this failure it is recommended that tests be performed to determine the stress limitation as the diameter changes. Until those tests are completed the stresses in mortar lined pipe should be limited to 18 ksi. In addition, if a pipeline is to be subjected to fluctuating levels of stress the pipe lining must be chosen carefully. The best choice for the lining would be a flexible lining but a mortar lining reinforced with welded wire fabric reinforcing may also be a choice.

THE PIPELINE

The Etiwanda Pipeline connects the Rialto Feeder to the Upper Feeder. The pipe is a welded steel pipe with a mortar lining. The pipe is approximately 6.5 miles long. The portion of the Etiwanda Pipeline inspected was between the Rialto Feeder and the Etiwanda Reservoir. In this portion of the pipeline the lining has failed. The portion of the Etiwanda Pipeline downstream of the reservoir was recently inspected and is undamaged. That portion of the pipeline has much lower head and is operated at a fairly constant pressure.

Power Generation

The Etiwanda Pipeline provides State water via the Rialto Pipeline to the Etiwanda Power Plant which then flows into the Upper Feeder. The Etiwanda Power Plant is currently being used in the peaking mode to maximize power generation revenues. In order to maximize power generation revenues, the flow through the turbine is varied daily. During the day, the flow is maximized to increase the amount of power that can be generated. During the night, the flow is reduced producing less energy. The result of this high flow/low flow operation and accompanying friction loss is that the pressure in the pipeline varies significantly daily. As can be seen from the graph, the pressure near the Etiwanda Power Plant (see Figure 1) varies from 250 psi to 300 psi daily. The steel cylinder stress at this location varies from 20 ksi to23 ksi daily. Near the Etiwanda pipeline turnout at Station 14+00 the pressure varies from 50 psi to 90 psi daily. The stress at this location varies from 8 ksi to 14 ksi.



Pressure and Stress Data in 2007 near Rialto Feeder (Sta. 14+00) - Figure 1

Inspection Results

After reports of large mortar lining failures from operations staff, Engineering staff from the Metropolitan Water District visually inspected 5.3 miles of the Etiwanda Pipeline Between December 16, 2008 and March 5, 2009 to evaluate the condition of the internal mortar lining. The inspection teams found:

- 245 locations with missing and delaminated mortar lining that ranged from 1 foot to 400 feet in length and an affected area varying from 1 ft^2 to 7500 ft^2.
- Approximately 37% of the 5.3 mile inspected length had missing or delaminated mortar.
- Most of the missing or delaminated mortar was in the top half of the pipe surrounding the crown.
- Most of the non-delaminated lining had several longitudinal cracks around the circumference, with a higher concentration of longitudinal cracks near the crown.
- In areas where the mortar was missing or delaminated the steel appeared heavily corroded.

Case Histories of Similar Failures

After inspecting the pipe, MWD conducted an investigation to determine if this type of lining failure had ever occurred in a pipeline comparable to the Etiwanda Pipeline in terms of size, lining, design stresses, and operation within the water industry. Northwest Pipe Company and Ameron International both examined their sales records but could find no instances of a similar failure. An extensive literature search showed that there were three other reported instances of failed mortar lining but the cause of the failures in those cases were not the same. In the first case, the Los Angeles Department of Water and Power reported a lining failure and repair of the Antelope Valley Siphon. However this pipe is a partially exposed aqueduct which is subjected to extreme fluctuations in temperature. The temperature fluctuations were the most likely cause of the failure especially since the siphon in most instances does not flow full. [i] In the second case, a pipeline in Saudi Arabia had corrosion beneath the cement lining of a pipeline. However, that pipeline transmits salt water to a desalination plant, so the corrosion is likely the result of the high Cl- ion content of the water [ii]. In the final case, a penstock mortar lining was repaired after being in service for 90 years. In that case, the mortar repairs were to the gravity-flow portions of a cast-in-place concrete lining[iii]. Based upon this research, there are no other case histories of similar failures of field-applied cement-mortar lining in large-diameter pipelines.

Construction History of Etiwanda Pipeline

To determine if the cause of the failure was poor construction the construction records of the Etiwanda Pipeline was examined.

Fabrication

The MWD constructed the Etiwanda Pipeline between 1991 and 1992. The pipeline is welded steel is 144 inch in diameter. Ameron International fabricated it in its Slover Avenue plant. The pipeline has a field applied cement-mortar lining of 3/4 inch and a cold-applied tape coating. The pipeline joints were coated with heat shrink sleeves.

Installation of Mortar Lining

The mortar lining was applied in the field. The mortar lining subcontractor used their projection method lining process in the straight runs and shotcreted the fittings because the lining machine couldn’t pass through 45 and 90 degree bends. In the projection method used, the mortar was centrifugally field applied by a spinning head that had 4 trowels on arms connected to the head. The mortar was flung out of the head, the trowels hit it once or so and the machine moved on. The pipe was divided off with Visqueen bulkheads and the mortar lined sections were water cured (the duration of the cure is uncertain; perhaps a week per section). The pipe for the most part was elongated 1inch vertically except in the area near the control facility manifold because the thicker pipe wasn’t flexible enough.

The mortar lining subcontractor took approximately 15 weeks to line the first 1000 feet of the Etiwanda Pipeline at the upper end because every time they completed that section the lining would fall out. In order to prevent lining fallouts an accelerator was painted on the upper half of the pipe. Once this process was perfected they proceeded to line the entire pipeline. There were other small fallouts but nothing compared to the early failures. Ahead of the lining all the bell and spigot joints were hand-filled with mortar.

Mortar samples were regularly taken. The lined sections were regularly checked for thickness by drilling a ¼ inch hole through the mortar and checked with a tire tread gauge. The mortar didn't have any voids between the mortar and the pipe. There was some cracking of the lining, some wide cracks were repaired but most of the cracks closed up after the hydrotest. The mortar lining was constructed per specifications and had acceptable quality.

Backfill Compaction and its Effect on Lining Performance

The pipe zone backfill compaction inspection records were examined. The pipe backfill was examined because if the compaction was inadequate the pipe's crown would deflect downward. If that happened, then the lining in the crown would be subject to bending stress. This could be a potential cause of the lining to failure. The construction inspection records show the pipe zone relative compaction to be very high, sometimes in excess of 100 percent. Metropolitan's 2009 lining inspection results were plotted on the profile to determine if there is a correlation between soil stiffness and lining failure. There appears to be no correlation between noted damage and the percent relative compaction of the backfill. That conclusion is also supported by measurements of pipe out-of-roundness. The pipe is substantially round. It must be concluded that stiffness of the pipeline backfill did not contribute to the collapse of the lining. Seismic and local settlement are probably not a potential cause of the lining failure.

Design Criteria: Steel Stress and D/t Ratio

"Steel Pipe – A guide for Design and Installation, M11" published by AWWA recommends that stress levels on steel pipe be kept to half of yield stress of the steel plate. On Table 4-1[iv] of M11 (fourth edition) it is recommended that steel pipe with mortar linings and coatings not be designed with a stress over 18 ksi. In previous editions of M11 there was no stress limitation clearly stated except that the stress should not exceed 50% of yield. The design stresses in steel pipelines were historically comparable to the yield stresses in available steel, while keeping the factor of safety at 2.0. Thus, for the typical 30-ksi steel, the design stress would have been 15 ksi. With no reason to assume a problem, the allowable stresses were generally raised to 16.5 ksi when ASTM A283 Grade D became readily available. In the late 1980's high strength steel became available. A paper[v] promoting the use of higher strength steel was published in the ASCE Pipeline Division Conference proceedings; however, it did not address what effects the higher strengths had on the lining. Rather, the paper concentrated on utilizing much higher design stresses in order to utilize the higher strength steel and reduce construction cost.

Prior to the Etiwanda Pipeline, MWD designed steel pipe to a maximum of 16.5 ksi. However, on the Etiwanda Pipeline, Metropolitan designed the pipe for a steel stress of 25 ksi. The reason the Etiwanda Pipeline was designed with an allowable stress of 25 ksi was because problems with PCCP had begun to surface about the time of the Etiwanda Pipeline was being designed. At that time, PCCP was cheaper to build and install than steel pipe. The designer recognized that steel pipe was superior to PCCP and the designer knew that steel with yield strengths of 50 ksi was readily available. In order to make steel pipe more competitive with PCCP the higher yield strength steel was used.

Etiwanda pipeline was also designed using a maximum D/t ratio (Diameter divided by pipe wall thickness) equal to 288. This was more conservative than M11 required when the pipe was designed. M11 recommended a D/t ratio of 350 at the time the Etiwanda Pipeline was designed. MWD and AWWA now use a maximum D/t ratio of 240. This means that the minimum wall thickness on the Etiwanda pipeline is ½ inch thick. The difference in D/t ratio has two effects. First, a thin walled pipe is harder to install due to its increased flexibility. Second, the pipeline will deflect more under the dead load of soil. As the out of roundness of the pipe increases the stress in the mortar lining will also increase. It is not believed that D/t ratio had any effect on the mortar lining failure of Etiwanda Pipeline.

Design Criteria: Maximum Deflection

The Etiwanda Pipeline was designed with a ¾ inch thick mortar lining. The lining was field applied after the pipeline was installed and backfilled. The deflection of the pipeline was limited to 3% considering the stiffness of the steel plate of the pipe only. AWWA recommends a maximum deflection of 2% for mortar lined pipe. AWWA allows the designer to consider the stiffness of the mortar lining. MWD's deflection criteria are approximately equal to AWWA's recommendation. It is not believed that excessive deflection is responsible for the lining failure. Field measurements found the lining within AWWA's recommended deflection criteria.

PROBABLE EXPLANATION FOR DAMAGE TO LINING

Stress on the Mortar lining

Mortar lining has been used on steel pipe since the 1920's. Mortar lining provides a smooth, dense finish that protects the pipe from corrosion. Mortar is a brittle material with a low tensile strength. The onset of microcracks in mortar will begin at a strain of about 135µ in/in. The onset of visible cracks takes place at about 1080µ in/in[vi]. The strain levels in a pressure pipe with an allowable stress of 16,500 psi is about 550 µ in/in. As can be seen from Table 1, the steel strain in any pressure pipe is much higher than the concrete tensile strain.

Table 1						
Steel			Mortar			
Es	σ_s	σ_s/Es	Em	$f'_{ten} = 7\sqrt{f'_m}$	$\frac{f'_{ten}}{E_m}$	$\frac{8f'_{ten}}{E_m}$
modulus of Elasticity ksi	Stress Level psi	Steel Strain µ in/in	modulus of Elasticity ksi	tensile strength psi	strain to start micro cracking µ in/in	strain to start visible cracking µ in/in
30000	16500	550	3840	519	135	1080
30000	21000	700	3840	519	135	1080
30000	25000	833	3840	519	135	1080

So how does mortar survive in any pressure pipeline? There are two factors which allow it to survive. The first factor is that when mortar lining is placed in service, water is absorbed into the pores of the cement and into the capillary channels of the calcium silicate gel. The water absorbed causes the lining to swell. The Ductile Iron Pipe Research Institute states that the lining will swell back to its initial volume (the volume it had prior due to curing shrinkage)[vii]. This process will restore the lining's intimate contact with the pipe wall and virtually close any cracks present in the lining due to shrinkage. This swelling process is relatively slow, taking up to several weeks for the lining to be restored to its maximum volume[viii].

The second factor that allows mortar lining to survive in a high pressure pipeline is autogenous healing. Small cracks are inevitable in mortar lining due to mortar shrinkage, temperature changes, handling and ring deflection. These cracks are not usually a problem because of the effect of autogenous healing. Autogenous healing is a process that occurs due to the formation of calcium carbonate and the continuing hydration of cement grains in the lining. After a period of exposure to water not only does the lining tighten against the pipe wall due to swelling and the cracks close but the cracks eventually heal. This healing is a phenomenon long recognized by the concrete industry. Any cracks that might remain slightly open due to inadequate swelling are subsequently closed by the formation of calcium carbonate. Autogenous healing will not only heal the cracks but the cement on both sides of the crack will eventually knit back together. Any cracks that remain open due to inadequate swelling are closed due to autogenous healing. Evidence of autogenous healing is a whitish substance forming along the crack line. AWWA C208[ix] permits cracks up to 1/16 inch wide to go unrepaired because autogenous healing will eventually close them.

Field inspections of lines that have been in service for many years have verified the laboratory results; cement linings do tighten and heal in service and provide the corrosion protection to the pipe and the high flow coefficients for which they were designed.

The Welded Steel Pipe Manual[x] has a formula to estimate the width of cracks. On the Etiwanda Pipeline the maximum crack width could be as much as those shown in Table 2. However this assumes that all deformation occurs at just two cracks. In general the guidelines in the Welded Steel Pipe Manual indicate that the cracks will be more uniformly spaced and the mortar will expand under the pressure to close many of the cracks. But it is easy to see that with an allowable stress of 25 ksi the cracks could be well in excess of 1/16 inch.

Table 2: Crack Width

Es	σs	σs/Es
modulus of Elasticity ksi	Stress Level psi	Crack width (inches) $w=\pi/2*D*\sigma s/Es$
30000	16500	0.1244
30000	21000	0.1583
30000	25000	0.1885

Considering the width of the possible cracks it is easy to see why the liner would fail if the pipe does not heal.

What is causing the problem?

The first factor is that the pipe was designed with a high allowable stress. Since mortar is unable to accommodate the radial elongation it will see due to the 25 ksi stress level it will crack. These cracks must heal if the lining is to survive long term. The damage to the mortar lining is less in the region where the stress is lower. Table 3 shows that in the regions with stress less than 16 ksi there is only 6% loss of the lining compared to 40% in every other reach of the pipe. Considering the width of the possible cracks it is easy to see why the liner would fail if the mortar lining does not heal. The lining is unable to survive as an arch with such a long span and such wide cracks.

Table 3 : Stress Level at Various Locations on Etiwanda Pipeline

Station numbers		Surface Area Missing Mortar	Elevation at downstream station	plate thickness inches	Average Pressure in feet of head	Average Stress ksi
1+36	36+83	6.70%	1560	0.50	250	15.60
36+83	86+52	43.90%	1440	0.63	370	18.47
86+52	110+83	35.00%	1382	0.72	428	18.58
110+83	146+85	35.10%	1320	0.78	490	19.57
146+85	185+68	33.20%	1250	0.88	560	19.97
185+68	219+00	51.20%	1215	0.94	595	19.80
219+00	227+53	15.20%	1206	0.94	604	20.10
227+53	259+00	60.40%	1210	0.94	600	19.97
259+00	268+23	33.70%	1170	0.97	640	20.61
268+23	283+71	44%	1165	1.00	645	20.12

The second factor is the Etiwanda Pipeline is a very large diameter pipe compared to most pipes. The diameter of the pipe will result in larger cracks than smaller pipes with similar stress levels. Even when a pipe has been designed to meet AWWA criteria, caution should be used when applying AWWA criteria to very large diameter pipe. Stressing a smaller diameter pipe (say 48 inch) to 25 ksi may not be a problem, but it may cause a problem when stressing a very large diameter pipe (say 144 inch) to 25 ksi. The total radial elongation for 144 inch pipe is 3 times of that for 48 inch pipe, and the corresponding crack width is also 3 times that of a 48 inch diameter pipe. For this diameter of pipe even under low stress levels the crack width may be significantly larger than 1/16 inch. The crack widths shown in the table may be distributed over several cracks but even then the resulting cracks could be more than 1/16 inch wide. Such large crack widths will cause the mortar arch to fail under the effects of gravity.

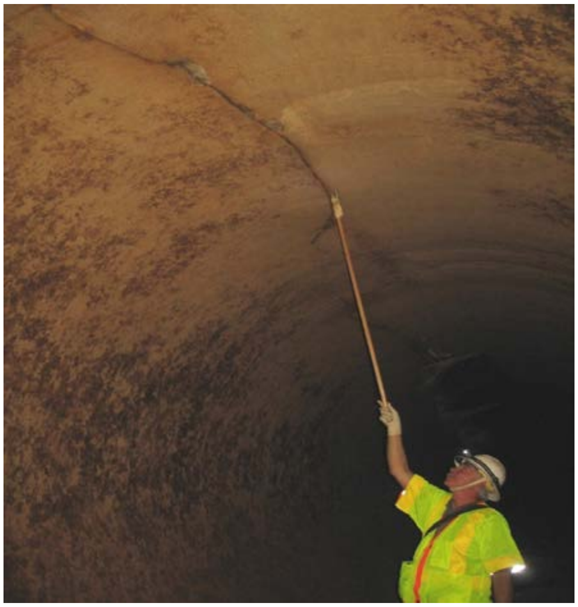
The third factor affecting the pipe is repeated cyclical loading. Although no literature was found on the effects of cyclical loading on mortar lining it is easy to see how this could severely affect the pipe lining. The cyclical loading is probably inhibiting the healing of the mortar lining.

This would eventually result in delamination of the mortar from the steel pipe. Once the lining is delaminated the mortar lining has to support itself as a concrete arch and failure is inevitable.

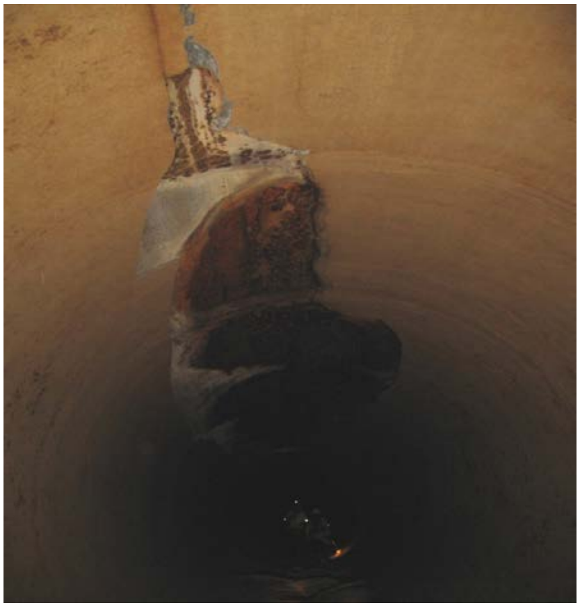
The final factor that may be affecting the pipe occurs after the mortar is delaminated from the pipe wall. It is possible that a differential pressure may develop between the water inside the pipe and the water behind the lining. If both the steel cylinder and the cylinder of mortar were completely disbonded, the expansion of the steel away from the mortar would occur at the crown of the pipe. Before the mortar fails it would remain in place only because it is supported by a combination of buoyancy and thin-shell arching. When the pipe is pressurized the radial expansion of the steel, (unconstrained by soil) would be $\delta = pr^2/Et$. This means that in an area where the pressure is 300 psi, the radial expansion would be $\delta = 0.050$ inch which cause a 0.10 inch (approximately 1/8 inch) gap between the steel and mortar. Because the mortar is porous, much like an open cell sponge, water between the mortar and steel cylinder would be expected to be at the same pressure as inside the lining. However if the pressure changes a differential pressure could develop for a short period of time. This differential pressure would cause additional cracks in the lining and accelerate the lining failure. After a sufficient number of cycles mortar pieces would begin to fail. This would cause adjacent sections mutually dependent upon the thin-shell arch for support to eventually fail.

Considering the length of the arch, the thickness of the mortar lining, the pipeline stress, the potential crack size, the frequency of the pressure changes and the inability of the pipe to heal, it is easy to see how the lining is failing.

The high stress level and diameter of pipe may not cause the failures we are seeing on Etiwanda Pipeline. However when combined with frequent changes in the pressure, the lining is unable to survive in the high stress regions and has even had failures in the lower stress regions.



Failure Begins as Longitudinal Cracks Develop Along Crown of Pipe.



As Mortar Cracking Progresses Small Pieces of Mortar Fall Out of Crown of Pipe.

Mortar Lining Failure Progresses After Initial Failure.

Exposed Steel Pipe is Unprotected and Begins to Corrode.

Recommendation

In view of this failure it is recommended that tests be performed to determine the stress limitation as the pipe diameter changes. Until those tests are completed the stresses in mortar lined pipe should be limited to 18 ksi. In addition, if the pipeline is subjected to fluctuating levels of stress the pipe lining must be a flexible lining. Mortar lining reinforced with welded wire fabric reinforcing may also be a choice if the welded wire fabric is adequately adhered to the pipe wall.

MWD is still evaluating how to repair the lining. Some of the options MWD is considering are mortar lining with welded wire fabric reinforcement and flexible coatings such as, high solids epoxy and polyurethane.

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[i] Final report – Los Angeles Aqueduct, Board of Public Service Commissioners of the City of Los Angeles, Second Ed. Oct 1, 1916, p. 22.

[ii] Water Transmission Line Failure at Aziziya Plant,‖ Dr. Annees U. Manlik, Research & Development Center, Saline Water Conversion Corporation, P.O. Box 8328, Al-Jubail -31951, Saudi Arabia, Tel +966-3-343 0333, Fax + 966-3-343 1615, e-mail rdc@swcc.gov.sa (July 1989). 5

[iii] Dental' job in Nevada's Greenhorn Mountains‖ Tunneling & Trenchless Construction magazine, March 2006, pp 12-14.

[iv] AWWA-M11 "Steel Pipe – A Guide for Design and Installation" Fourth Edition.

[v] The Effects of High-Strength Steel in the Design of Steel Water Pipe,‖ Robert J. Card and Dennis A. Dechant, Second International Conference on Advances in Underground Pipeline Engineering, Bellevue, WA, June 25-28, 1995, ASCE, ISBN 0-7844-0093-8, 1995

[vi] AWWA C304 Figure 2

[vii] American Ductile Iron Pipe "Cement Mortar Linings for Ductile Iron Pipe" By Richard Bonds DIPRA Research/ Technical Director

[viii] American Ductile Iron Pipe "Cement Mortar Linings for Ductile Iron Pipe" By Richard Bonds DIPRA Research/ Technical Director

[ix] "Cement -Mortar Protective Lining and Coating for Steel Water Pipe – 4 in and larger – Shop Applied"

[x] American iron and steel institute