Case Study: Condition Assessment

CONDITION ASSESSMENT OF ASBESTOS CEMENT WATER MAINS, CITY OF SAN DIEGO, CALIFORNIA

Report Created By: Mr. Bhaskar Dasari, Virginia Tech

Principal Investigator: Dr. Sunil K. Sinha, Virginia Tech

External Reviewers:

June, 2015

DISCLAIMERS

This research is funded through the Virginia Tech's Sustainable Water Infrastructure Management (SWIM) Center's research agenda that supports efforts to put the nation's aging infrastructure on a pathway toward sustainability and resiliency.

This case study was prepared by Virginia Tech as a part of the WATERiD project. Neither Virginia Tech, SWIM Center, members of SWIM Industry Advisory Board, external reviewers, nor any person acting on their behalf: (a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this case study report or that such use may not infringe on privately owned rights; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, method, or process disclosed in this case study report.

A panel of independent experts selected by SWIM Center reviewed this document. Mention of trade names or commercial products do not necessarily reflect an endorsement or recommendation for use by Virginia Tech. Similarly, omission of products or trade names does not indicate the position of Virginia Tech regarding product effectiveness or applicability.

ACKNOWLEDGEMENTS

The research team is grateful for the support from the SWIM Industry Advisory Board. The authors also acknowledge the contribution of the utility, and technology providers for providing their comments and feedback in an effort to successfully conduct this research project. Special thanks to the following individual(s) for providing data, information, and their valuable comments and feedbacks:

- Mr. Jerome Potenciano, Public Utilities Department, San Diego, California
- Mr. Eric Rubalcava,Public Utilities Department, San Diego, California
- Ms. Celine A. Hyer, ARCADIS US., Inc., Tampa, Florida

Table of Contents

LIST OF FIGURES

LIST OF TABLES

CASE STUDY SUMMARY

From February 2014 to August 2015, ARCADIS U.S., Inc. was contracted by City of San Diego to develop the Asbestos Cement (AC) Water Main Replacement Program Master Plan for the City of San Diego. Extensive literature review of the AC pipe replacement studies was conducted to guide the project methodology. The existing data of City of San Diego was reviewed to establish service levels, consequence of failure and pipe replacement costs to facilitate risk scoring and replacement planning. Subsequently, evaluating the structural integrity of selected asbestos cement distribution mains fills the gaps in pipe data and break analysis. ARCADIS approached Echologics to gain information on critical portions of asbestos cement distribution mains in the City of San Diego. To achieve these objectives, Echologics utilized the ePulse™ condition assessment method with the LeakFinder™ correlator to determine the current condition of the pipe walls and locate leaks.

A forecasting model using the LEYP algorithm was built to predict the likelihood of failure for each AC pipe. The resultant data from the non-invasive acoustical pipe testing, soil sampling and AC pipe material analysis was used to calibrate the statistical failure-forecasting model and validate the selected projects. The results from the forecasting modeling, consequence of failure evaluation, and unit replacement costs are utilized to conduct a risk analysis. Consequently, a GIS planning tool will be developed to plan and track the R & R projects by assigning the risk scores to identify and group projects. To sustain the replacement program, ARCADIS developed an effective training and knowledge transfer program on the LEYP model and the GIS tool.

KEYWORDS

Asbestos Cement Mains, Service Levels, Forecasting Model, Effective Useful Life, Smart Data, GIS Planning Tool

LIST OF ACRONYMS

AC	Asbestos Cement
CA	Condition Assessment
COF	Consequence of Failure
EUL	Effective Useful Life
GIS-RPT	Geographic Information System-Replacement Planning Tool
LEYP	Linear Extended Yule Process
LOF	Likelihood of Failure
MGD	Million Gallons per Day
YOB	Year of Break
YOI	Year of Installation

UTILITY DETAILS

Utility Name

City of San Diego

Figure 1: City of San Diego Logo

Service Area

The City of San Diego has more than 3,300 miles of water mains ranging in size from 4 to 24 inches in diameter with an average daily demand of 171 million gallons per day. More than 2,120 miles of the City's water mains consist of asbestos pipes that are reaching the end of their useful life and are experiencing an increase in breaks and leaks.

Size and Budget

The City of San Diego provides water distribution and treatment services to approximately 1.3 million residential and commercial users. The total length of the pipeline in the utility is approximately 2100 miles. The average daily water production is 161 mgd. The material of the pipeline in the utility is Asbestos Cement. The annual operating budget of the utility is $462,671,644. The annual capital budget of the utility is $100,151,601 and the annual budget for condition assessment is $5 to 7 Million.

Assets

The construction and maintenance division of City of San Diego Public Utilities department maintains approximately 274,000 metered service connections, approximately 24,000 fire hydrants and more than 46,000 isolation valves.

The systems operation division of City of San Diego Public Utilities department maintains three water treatment plants, 49 water pump stations, 31 treated water reservoirs and more than 950 water regulators. The water treatment plant capacity is 328 mgd.

Mission and Vision Statements - Public Utilities department

Mission

"To ensure the quality, reliability, and sustainability of water, wastewater and recycled water services for the benefit of the ratepayers and citizens served."

Vision

"We are an industry leader in the delivery of water, wastewater and recycled water services."

CASE STUDY FOCUS

This case study focuses on the Condition Assessment (CA) and Effective Useful Life (EUL)evaluation of the Asbestos Cement Mains of City of San Diego. The process of reviewing the existing pipeline data, and filling the data gaps through pipe testing and soil testing is highlighted. The technologies used in the process of identifying the critical areas with high levels of degradation in the mains are also presented.

ASSETS CONSIDERED IN THE PROJECT

This case study centers on the assessment of over 2100 miles of AC water mains. It is composed of 4-24-inch diameter. The field-testing consists of two phases totaling 39 miles of asbestos cement pipe. Phase I included73,339 feet of 16-inch asbestos cement mains distributed over nine distinct areas of the city, as shown in Figure 2.

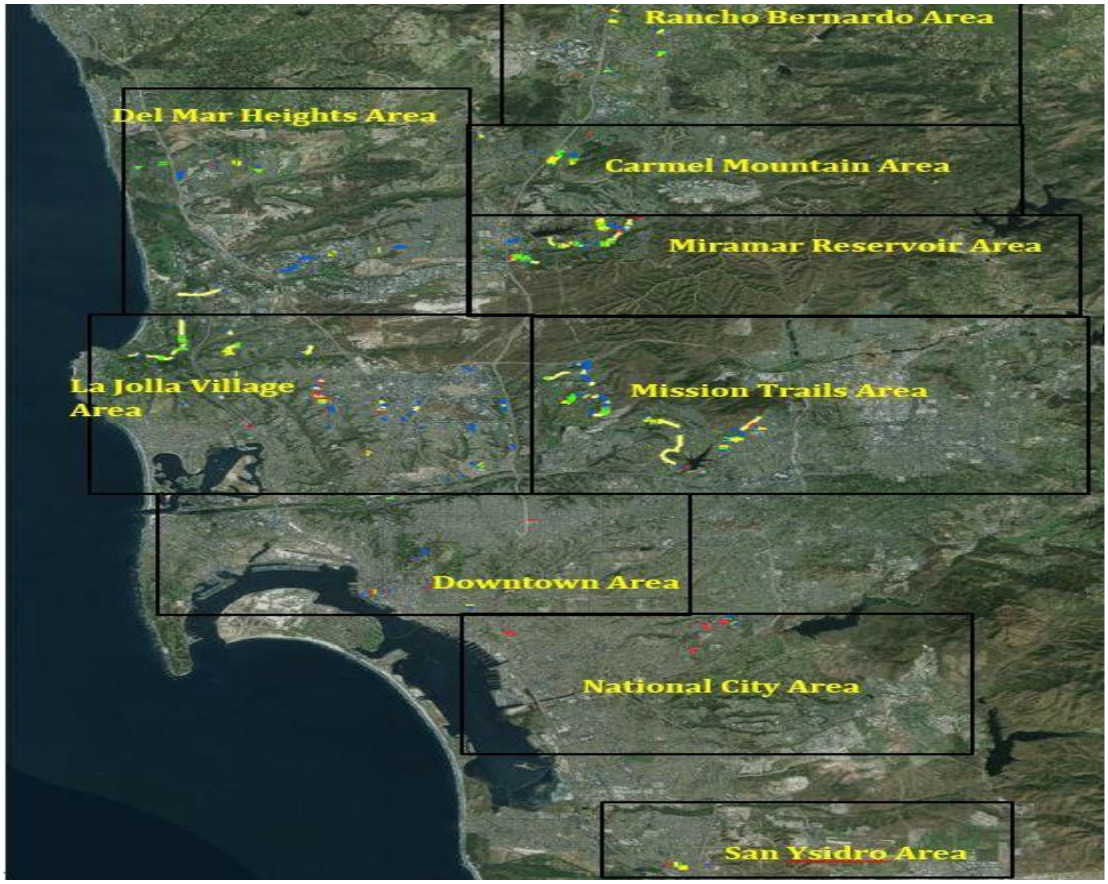

Figure 2: Site Locations

KEY DRIVERS

The City of San Diego water mains consist of more than 2100 miles of asbestos pipes which are experiencing a rise in pipe breaks and leaks and are reaching their end of useful service life. An AC Master Plan was devised to test pipe cohorts to get data on all pipe ages pertaining to AC mains. The developed Master Plan identified the need for condition assessment data. This prompted the requirement to establish a condition assessment program. The key factor to implement the condition assessment program was to reduce the risk associated with main breaks. Also, understanding the effective useful life of pipelines and creating a plan for replacement was the main purpose of establishing a condition assessment program. The data collection aspect of the condition assessment program will fill critical data gaps such that final definitions of AC pipe cohorts and their effective useful life can be made. Furthermore, the data determined by performing AC pipe laboratory analysis will provide information to use in the analysis to assist with defining specific risk factors and failures modes and refine effective useful life.

KEY FEATURES OF THE PROJECT

ARCADIS US, Inc. was contracted to review the existing data including the GIS water system layers, break history, AC pipe samples, scoring criteria, and related soil conditions and other risk factors for City of San Diego, CA. This system data evaluation and analysis was used in establishing service levels and consequence of failure parameters. The methodology involved in the consequence of failure evaluation criteria and scoring approach is discussed in this case study.

Furthermore, the application of the selected service levels for the replacement master plan is also discussed. Pipe replacement costs was analyzed to facilitate risk scoring and replacement planning. The review and analysis of the main and break data identified the gaps in the data. A field investigation program was setup to address these data gaps in terms of identifying main groups with insufficient break data. Areas where field-testing should be conducted to evaluate the likelihood of failure was determined to fill the data gaps.

CONSEQUENCE OF FAILURE SCORING

Risk and Triple Bottom Line Analysis Approach

The important aspect of condition assessment is the risk evaluation, because it is a key factor in prioritization of technologies based on perceived value. Risk is defined as the consequences of failure times the likelihood of failure. In any program of condition assessment and prioritization, it is necessary to determine not only the likelihood, but also the consequences of failure. COF accounts for the criticality of an AC water main related to failure impacts based upon a triple bottom line approach. This approach considers economic, social, and environmental factors to define specific criteria and evaluate the impact.

Consequence of failure scoring describes the qualitative triple bottom line approach applied to analyze the AC mains based on, economic, social, and environmental factors. These categories are evaluated based on existing San Diego pipe attributes and available GIS layers that identified adjacency factors including the following:

- Economic – Direct Cost to Repair
  - Pipe Diameter
  - Soil slope
  - Pressure
- Social – Impacts to Society and Customers
  - Critical Customers Served
  - Other Infrastructure (Roads and Rail)
  - Zoning/Land Use
- Environmental – Violations and Degradation to the Natural Environment
  - Environmentally Sensitive Lands

- Water Bodies

Pipe Scoring Criteria

Based on the available data sources, a scoring criteria was developed for each consequence of failure factor. The first step involves grouping of factors into three categories of increasing criticality: 1 = Low, 2 = Medium and 3 = High Consequence of failure. The highest score in any criteria then becomes the pipe initial COF score. In a second step, the score is increased through addition up to 5 if more than 1 criterion has medium or high scores for any single AC pipe. Additional distinction among the high critical pipes is achieved through this method and also the scoring range is expanded to 1 to 5. Tables 1 - 8 defines the COF Criteria results of the parameters and Figure 3 depicts the COF Results map.

Pipe COF Results

Table 1: Water Main Size COF Criteria Results

Diameter	Ranking	% Length
> = 16 inch	High	5.95
>8 and <16 inch	Medium	26.68
< = 8 inch	Low	67.37

Table 2: Static Pressure COF Criteria Results

Static pressure	Ranking	% Length
> 120 psi	High	23.97
>=80 and <=120 psi	Medium	53.49
< 80 psi	Low	22.54

Table 3: Soil Slope Size COF Criteria Results

Soil Slope	Ranking	% Length
> 50%	High	3.24
> 15 and <= 50%	Medium	33.54
< =15%	Low	63.21

Table 4: Critical Customer COF Criteria Results

Critical Customer	Ranking	% Length
Top 25Hospitals Military Airports	High	1.05
All other Critical Customers	Medium	1.60

Table 5: Land Use COF Criteria Results

Land use	Ranking	% Length
Industrial	High	2.62
Commercial Multi Family	Medium	8.82

Table 6: Proximity to Road and Rail Line COF Criteria Results

Other Infrastructure	Ranking	% Length
Within 100 feet of Freeways or Ramp	High	1.24
Within 50 feet of Rail Lines	Medium	0.32
Crossing Rail Lines	High	0.21
Crossing Prime or Major Arterial or Collector Roads	Medium	13.83

Table 7: Proximity to Water and Sensitive Land COF Criteria Results

Land use	Ranking	% Length
Crossing Sensitive Lands or Water Bodies	High	1.91
Within 100 feet of a Water Body	Medium	0.58

Table 8: Final Overall COF Scores by Pipe Length

Land use	Ranking	% Length
Very high	5	0.85
High	4	5.32
Medium	3	36.30

Low	2	48.39
Very Low	1	9.15

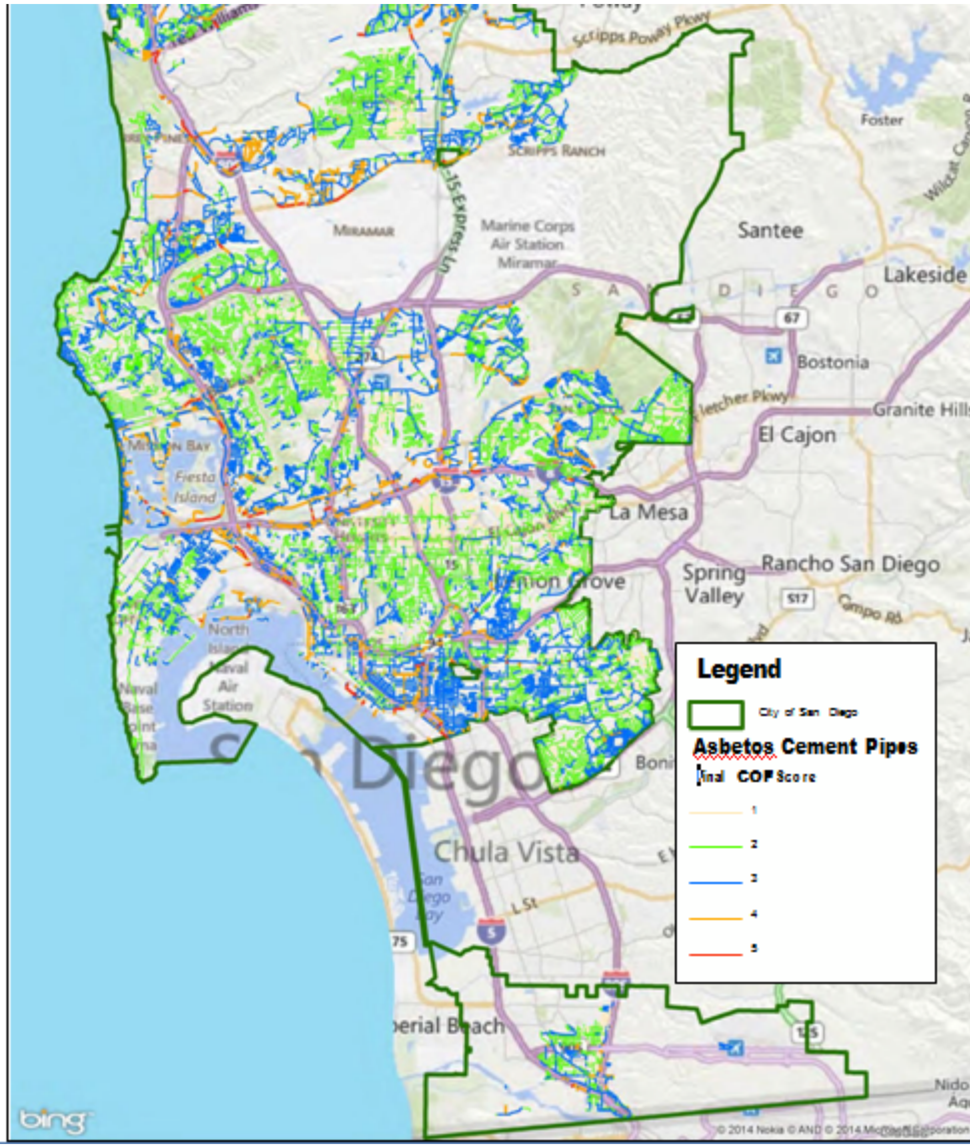

Figure 3: COF Results Map

REVIEW AND ANALYSIS OF AVAILABLE DATA

The risk factors of the AC mains were determined by conducting a statistical analysis. The category of mains that portray similar behavior in degradation are grouped together. This allows to prioritize candidates for field investigation, forecast future failures using the Linear Extended Yule Process (LEYP) forecasting model, evaluate the Effective Useful Life (EUL) of each cohort, and assign a LOF score to each main. The analysis required analyzing the available data based on the location and dates of occurrence of the breaks and leaks. Main and environmental data was reviewed to identify the factors of failure such as Date of Installation, Diameter, Material, Pressure and Soil Type.

Identifying the AC Mains

The AC Mains that can be used for the statistical analysis, their risk factors of failure, and the breaks that have occurred was identified. Only mains and breaks with complete and consistent attributes was kept for a statistical analysis. The data review consists of identifying, and assessing the quality of data on mains and their breaks. The overall statistical results of the AC Main pipes data are presented in Table 9.

Table 9: Length of AC Mains based on Life Status, Diameter and Year of Installation as of 2013

Mains	Active	Abandoned	Total
All	3,389.4	245.1	3,634.5
AC	2,128.2	51.83	2,189.0
AC diameter >= 4"	2,126.3	51.8	2,178.1
AC diameter >=4" no YOI	63.5	13.9	77.3
AC diameter >=4" YOI>1990	84.4	4.2	88.6
AC diameter >=4" YOI<=1990	1978.4	33.9	2,012.3

Analyzing the Breaks/Leaks in AC Mains

The City of San Diego maintains its work orders in a database called SWIM. This database was provided to ARCADIS for review. The failures defined as breaks in this database are categorized in the system as Problem code 724whereas leaks are categorized as Problem code 1161.

In 2013 the City of San Diego started a review of the SWIM data (breaks and leaks since 2007) in order to identify what events could be considered real breaks. SWIM data (since 2008) was also reviewed in order to distinguish what constitutes a break (SWIM code 724) from a leak (1161).A final list of 420 breaks/leaks is used for failure analysis.

FAILURE ANALYSIS

The data obtained from the analysis is used to determine the risk factors that influence the degradation of AC Mains. The failure analysis of the AC Main breaks is done with respect to time. Three different analysis pertaining to the length and break rate were conducted:

- Length and Break Rate based on the Year of the Break (YOB)

- Length and Break Rate based on Year of Installation (YOI)
- Length and Break Rate based on the age of the main at the YOB

Length and Break Rate based on YOB

Below are the assumptions used to develop the break rate based on YOB:

- Abandoned mains were included in the analysis. Since the Dates of Abandonment (DOA) were not available, they were assumed to be 2013. So, for this study, the abandoned mains were treated like active ones. Breaks that have occurred on active and abandoned mains are available since 2004until 10/23/2013 (9.8 years).
- The length of AC mains during that period of time was 2,178 miles. It was assumed that there are no new installations and no abandonments.
- Since break data was not available for the analysis year (2013), the break rate was adjusted for a 10-month period.
- Overall the average break rate over the 9.8-year period (from 2004) was 0.02 breaks/mile/year(420/2178/9.8) or 2-breaks/100 mile/year.
- The overall break rate when considering breaks since 2008 is 0.023 breaks/mile/year(274/2178/5.5) or 2.3 breaks/100 miles/year, slightly higher than what the City of San Diego had computed in 2013 when they evaluated the SWIM break records.
- AC mains have broken between 1 and 7 times and 98.7% of the mains have never broken at all. Figure 4 below shows the break rate every year since 2004.
- The break rate has been increasing over time.

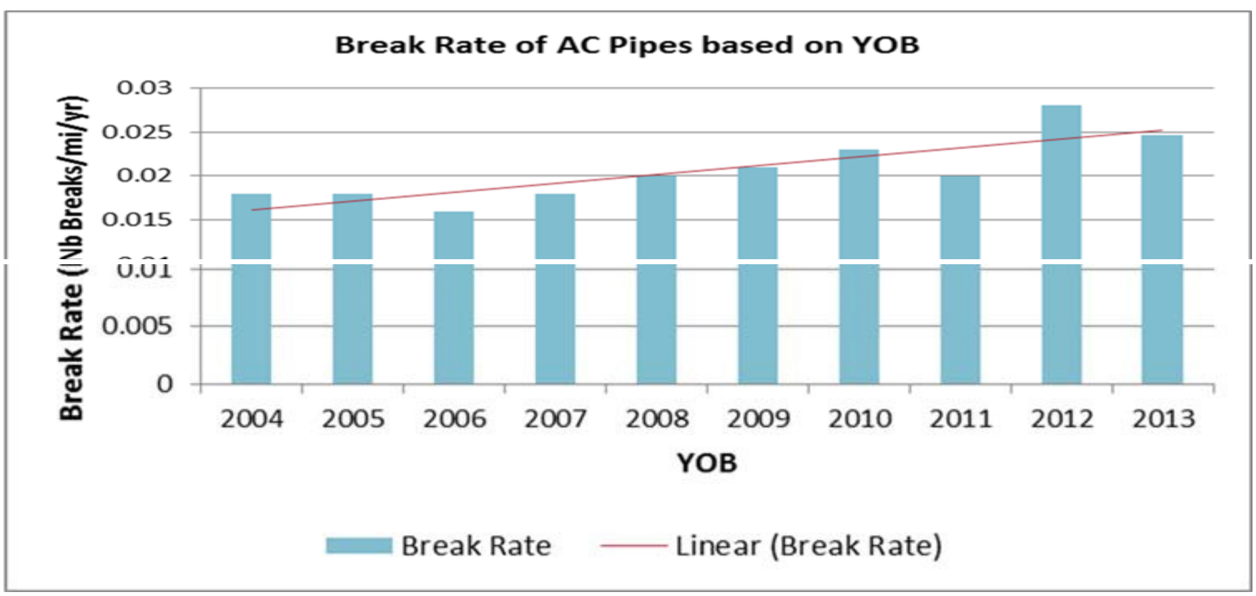

Figure 4: Break Rate of AC Mains Based on YOB(420 Breaks)

Length and Break Rate based on YOI

The majority of the AC main installation has occurred between 1950 and 1990. The break rate is shown to depend on whether the mains were installed before or after 1956. The rate is much higher on mains installed on or before 1956. Figure 5 shows the Break Rate based on YOI.

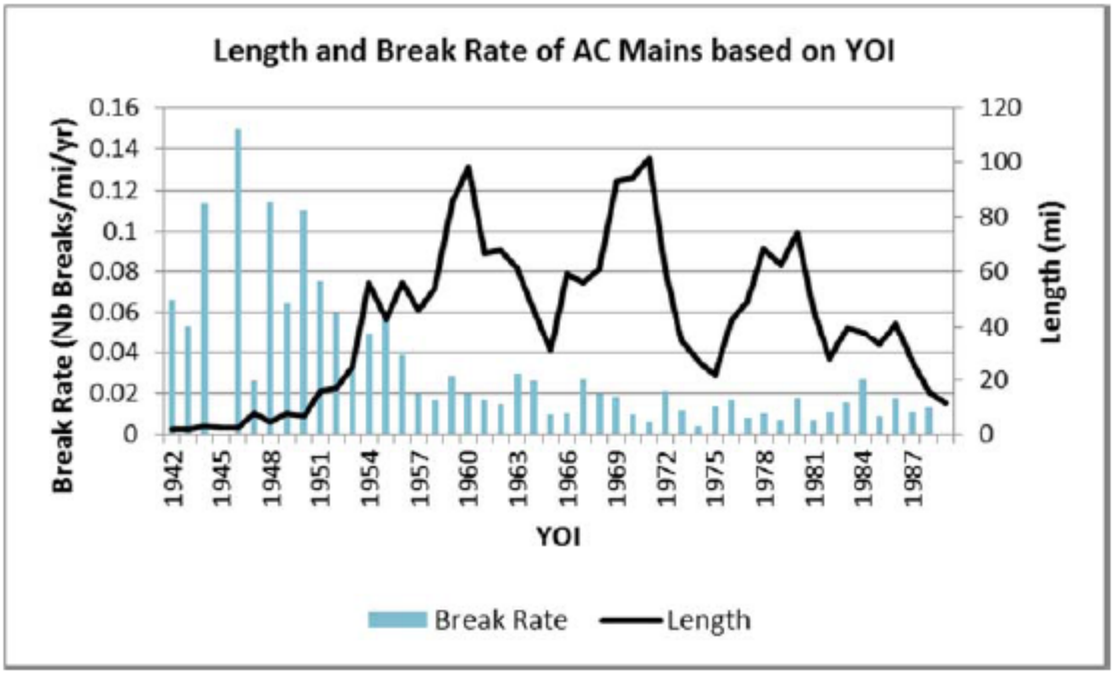

Figure 5: Length and Break Rate of AC Mains Based on YOI (420 Breaks)

Length and Break Rate based on Age at YOI

The last of the AC mains in the system were installed in 1990. By 2004, date of the first observation of breaks, the mains installed in 1990 was 14 years old. Therefore, Figure 6 starts at 14 years of age. Between the years 2004 and 2013 (period of observation of the breaks):

- Approximately 158 mi of mains reached the age of 14 with a break rate of 0.
- Approximately 1,200 mi of mains reached the age of 42 with an average break rate of approximately 0.01 break/mile/year or 1 break/100 miles/year.

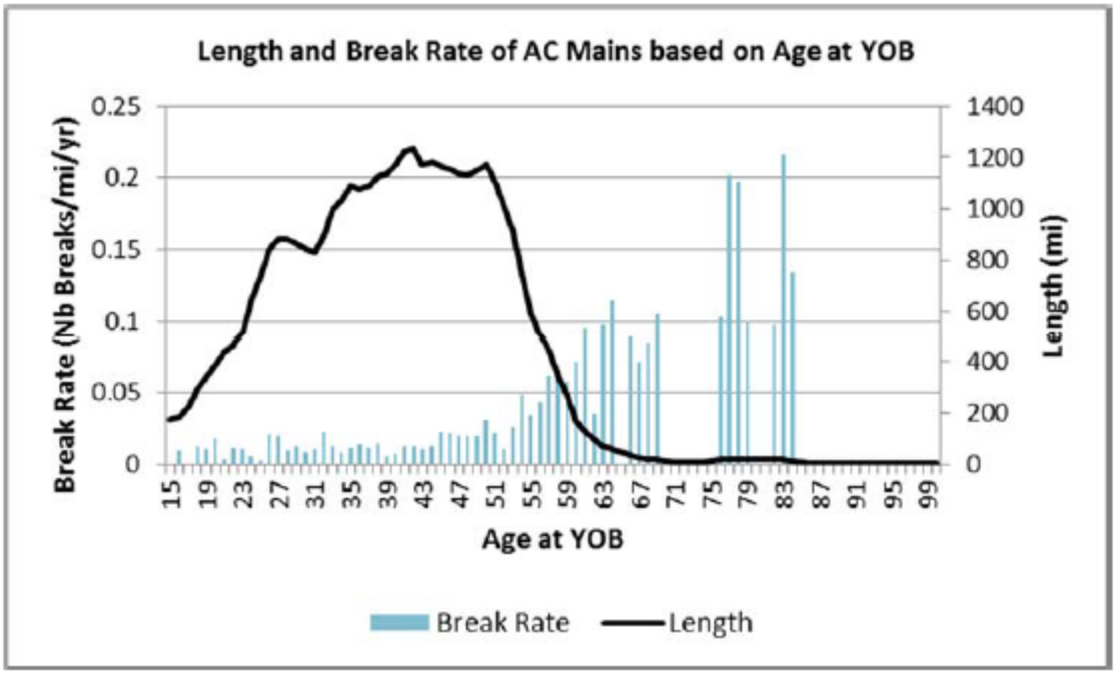

Figure 6: Length and Break Rate of AC Mains Based on Age at YOB (420 Breaks)

Figure 6 shows that the break rate is around .015-breaks/ mile/year or 1.5-breaks/100 miles/year for mains between 26 and 45 years. It starts to increase after 45 years (which is the average age of AC mains in 2013).And by 64 years, the break rate has increased to 0.1 breaks/mile/year.

Based on the extensive review of the City of San Diego GIS, SWIM database, and other sources, 420 breaks occurring between 2004 and 2013 were identified and used in the statistical analysis. Those 420 will also be used in the LEYP failure-forecasting model. The risk factor variables kept for the LEYP studies are:

- Year of Install (before and after 1956)
- Main Diameter (small, medium, or large)
- Average Pressure
- Soil (Urban or Not)

The data analysis shows that there have been very few breaks on the large diameter mains(mains greater than or equal to 16 inch). This will make it impossible to reliably forecast the failure of those mains. Furthermore, keeping those mains in a generic model would most likely skew results for the other mains. As a result, the field program focused on collecting data for these large diameter mains. Field data was used to estimate the EUL for the mains, as it cannot be evaluated through the forecasted failures.

WATER MAIN REPLACEMENT COSTS

In order to determine the financial forecast, planning level replacement cost opinions were determined for each main segment in the GIS replacement-planning tool. To develop these opinions, unit costs of replacement for every possible main size and material were established. The unit costs for the Main Replacement Program were developed based on available data including, recent projects with similar components, City of San Diego cost estimation procedure, vendors' budget estimates, standard construction cost estimating manuals, and engineering judgment. The Replacement Costs include:

- Mainline Costs: account for excavation, bedding, slurry sealed street, and mainline appurtenances.
- Soft Costs: include planning, preliminary engineering, surveying, project management, design, bid & award, construction management, and project close out.

The detailed calculation is shown in Figure 7.

Item	Material	Cost	Units	Construction Cost Index (2010)	Construction Cost Index (2014)	Contruction Cost (Sept. 2014)	Contruction Cost with Soft Costs[3] (Sept. 2014)	Contruction Cost with Soft Costs and Contingency[4] (Feb. 2014)	Included in Unit Cost	Source
Distribution Pipelines										
8"	PVC	$187	$/LF	8799	9870	$209	$278	$299		From City of San Diego
12"	PVC	$258	$/LF	8799	9870	$290	$385	$414		
16	PVC	$324	$/LF	8799	9870	$364	$484	$520		
Transmission Pipelines										
20"	PVC	$385	$/LF	8799	9870	$432	$574	$617		From City of San Diego
24"	CMLC Steel	$484	$/LF	8799	9870	$543	$722	$776		
30"	CMLC Steel	$530	$/LF	8799	9870	$594	$790	$850		
36"	CMLC Steel	$625	$/LF	8799	9870	$701	$933	$1,003		
42"	CMLC Steel	$770	$/LF	8799	9870	$864	$1,148	$1,235		

NOTES:

(1) September 2014 Costs (ENR CCI = 9870).

(2) Unit capital costs include engineering/design, materials of construction, installation and contractor overhead and profit.

(3) The soft cost are as following for pipeline replacement and include Planning, Prelimnary Engineering, Surveying, Project Management, Design , Bid & Award, Construction Mgmt and Close Out (33.33 percent)

(4) Contingency (10 percent).

Figure 7: Summary of Capital Unit Costs

FIELD PROGRAM

The field investigation was conducted in two phases. The Phase 1 program fulfils the critical data gaps by conducting a non-invasive acoustical wall integrity testing of AC mains. To confirm the specific risk factors and pipe failure modes, a laboratory analysis was performed on the main break samples. The locations of previous main breaks with significant wall loss were identified and soil testing was performed in those areas. Soil, as a risk factor is analyzed in this test and they are characterized in those locations.

The Phase 2 field investigation will occur after the LEYP model is built and AC main replacement plan is drafted. The LEPY model and the replacement plan is validated through the observations obtained from field investigations. Phase 2 field investigation will also involve, acoustical pipe testing, pipe laboratory testing and potentially soil testing, depending on the results of the Phase 1field program.

Roles and Responsibilities of the Stakeholders

Various subcontractors in different roles performed field investigation work and responsibilities as summarized in Table 10.

Table 10: Roles and Responsibilities

Company	Project Role
ARCADIS	Project management/project oversight/testing site selection
Arrieta Construction	Pipe sample pick-up and cutting
BBC Environmental	Soil testing and analysis
Corrosion Probe	Laboratory testing and analysis of pipe samples
Echologics	Acoustic pipe wall integrity testing
HDR	Literature review and QA/QC
Hudson Safe-T-Lite	Traffic control
infraPLAN	Data analysis, modeling, succession training
PARC Civil	Field reconnaissance
Proteus	Safety plan review, permitting support

The phase I field program includes:

- Field Acoustical Testing
- Soil Testing
- AC Main Break Sample Testing

Field Acoustical Testing

The acoustic testing is performed to understand the critical data gaps that define the category of mains that portray similar behavior in degradation, their effective useful life (EUL), and their decay curves. Review of historical AC main break data revealed the following:

- 2 breaks were found over the 3 miles of large diameter Type I (installed in or before 1956) mains which are the oldest, worst pipe type and highest criticality.
- 11 breaks were found over the 124 miles of large diameter Type II(installed after 1956) mains
- 165 breaks were found over 1,357 miles of medium diameter Type II mains

This indicated a lack of break data for large diameter mains. Therefore, the pipe condition data, especially, from Type II large diameter mains will fill the data gap by providing data needed to create the degradation curves for large diameter main where the LEYP model cannot be created.

Therefore, acoustical testing program for Phase 1 focussed on assessing the condition of large diameter mains to fill in this data gap.

The subsequent step is to select the acoustic testing locations. A desktop optimization process is carried out to identify pipe segments with valve distance suitable for testing (maximum of 400 ft. between two valves). Accessibility to pipes with regards to location of valves and traffic condition was determined from GIS map and Google Maps, respectively. Optimization is based on practicality factors. After the desktop selection was done, field reconnaissance verified the desktop selection by determining the accessibility of valves for testing. Table 11 summarizes the field reconnaissance recording for each test site.

Table 11: Field Reconnaissance Recording

Data Field	Description
Traffic Condition	High/low, number of lanes, residential/commercial
Inspection	Yes/No
Located	Yes/No
ValveCover	Can valve lid be opened? Yes/No
Access	Is valve accessible? Yes/No
Changed by	Initials of person doing the inspection
Change date	Date of inspection
ReconSelection	Include/Exclude for testing
ReconProblems	Reason why exclude for testing

Based on data gaps, traffic conditions, and field reconnaissance; 14.5 miles of the 16-inch AC mains of varying ages were selected to acoustically tested by Echologics during Phase 1 so that decay curves could be created. Table 12 summarizes the miles of AC mains selected based on Year of Installation (YOI).

Table 12: Miles of AC Mains Tested in Phase I

Year of Installation	<=1956	1957-1960	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	Total
16 inch	0.6	2.1	1.78	1.71	2.36	1.70	2.16	0.94	13.3
18 inch	-	-	0.18	-	-	-	-	-	0.2
20inch	-	-	0.13	0.48	0.15	-	0.14	-	0.9
24 inch	-	-	-	-	0.09	-	-	-	0.1
	0.6	2.1	2.1	2.2	2.6	1.7	2.3	0.9	14.5

Consequently, acoustic testing is done on-site which comprises two tests, one to detect leaks in the pipe and another to determine the average wall thickness.

ePulse™ condition assessment method with the LeakFinder™ correlator were utilized by Echologics to verify the condition of the pipe walls and detect the leaks. The current average minimum structural thickness for asbestos cement mains is measured through the ePulse™ condition assessment method. A noise source is created out-of-bracket i.e. at a location outside of the pipe segment undergoing testing. The acoustic wave velocity created by the noise in the pipe segment is measured. The acoustic wave velocity is found by dividing the length of pipe segment by the time taken for the acoustic signal to propagate between the two sensors. Results are shown as remaining effective structural thickness. Figure 8 depicts the effective wall loss over the year range of installation. Echologics' ePulse™ method provided leak detection as a secondary survey result. The test method involves attaching a noise sensor and Hydrophone onto the two valves. The two noise sensors are connected to a common leak noise correlator. The time delay between the two sensors is used to determine the position of the leak.

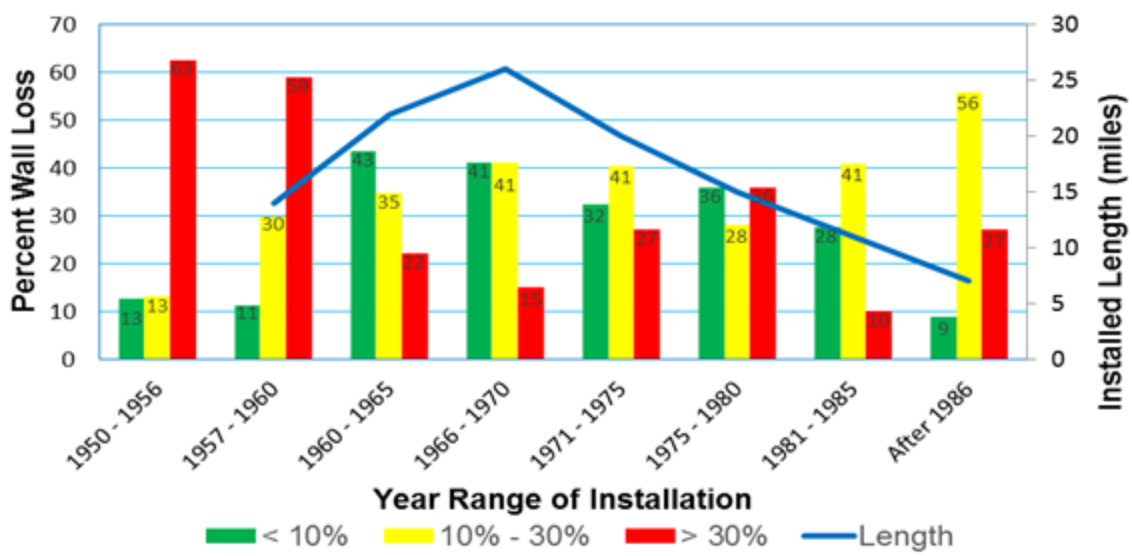

Figure 8: Year of Installation Vs. Effective Wall Loss

The following conclusions are drawn from the Phase 1 testing results of large diameter mains:

- Type I (YOI < 1961) show a greater percentage wall loss than Type II(YOI > 1961) AC mains
- Type II AC mains show a greater percentage wall loss in the southern regions of Downtown, National City and San Ysidro than in other regions in the City(refer Figure 1)
- Mains on Urban soils show a higher wall loss than mains on Non-Urban soils
- No apparent trends are seen between wall loss and age of pipe based on average pressure or soil type.

The following recommendations were used to develop a replacement plan for large diameter pipes:

- An Effective Useful Life (EUL) of 70 years is used for all large diameter Type I mains so that they are considered first in the replacement program.
- For Type II large diameter mains, published EUL values of 87 to 118 years (based on internal pressure) are used.
  - Since higher degradation was seen in the southern regions (Downtown, National City and San Ysidro), a EUL of 87 years is used for these areas.
  - Similarly, newer mains installed after 1981 also exhibited higher degradation and are assigned of a EUL of 87 years.
  - Mains on Urban soils indicated higher degradation and are assigned a EUL of 87 years.
  - All other Type II large diameter mains are assigned an EUL of 118 years

Soil Testing

The Phase I soil testing is performed to understand the contribution of the soil properties to the AC pipe degradation. A total of 40 soil sampling sites are selected for the Phase 1 testing. The locations are spread out over the region. Soil-testing locations are selected based on two conditions:

- Areas where historical AC main break has occurred
- Areas of poor AC main condition as indicated by the Phase 1 acoustic testing results.

The level of corrosivity and the chemical attack for the pipe material in contact with the soils is determined through soil analysis. The soil parameters and their method of analysis is depicted in Table 13.

Table 13: Soil Parameters and Their Method of Analysis

Parameter	Method of Analysis
Soluble cations (Ca, Mg, K, Na)	EPA 6010B
Soluble anions (Cl and SO4)	EPA 300.0
Soluble anions (NH3 and P)	SM 4500
pH	EPA 9045
Moisture content	ASTM D2216
Soil type	Sieve-laser combo ASTM D422/D4464

AC Main Break Sample Testing

The objective of the AC main break sample analysis is to assist with defining specific risk factors and failure modes and refine the Effective Useful Life (EUL) information. Ten samples were collected from various locations throughout the City of San Diego distribution system. The major objectives for laboratory testing of AC main samples were to:

- Verify the pipe nominal diameter and material class
- Assess the overall integrity of the main samples
- Identify potential modes of failure
- Determine root cause of failure
- Support the criteria developed for determining pipe replacement priority
- Refine the Effective Useful Life (EUL) of the AC mains in conjunction with acoustic and soil testing results

The following analyses were performed on the collected AC main samples, along with the reasons for these tests:

- Measure Outer Diameter (O.D.), Inner Diameter (I.D.) and wall thickness to determine nominal pipe size and pressure class
- Visual evaluation of general pipe condition and determination of best/worst areas of each sample with respect to compromised wall thickness
- Phenolphthalein test on specimens cut from the best and worst area of each sample
- The pH of slurry prepared with sieved powder from the O.D. surface, mid-wall thickness and the I.D. surface of each sample
- Measure sulfate (as sulfur trioxide) level at the O.D., mid-wall thickness and I.D. of each sample.
- Prepare polished full wall-thickness cross-section from best and worst areas of each sample followed by examination for micro cracking.
- Evaluation of relative hardness of pipe wall matrix across the polished cross-sections prepared for the micro-cracking examination

Based on various test results described above, the below conclusions were derived:

- All ten AC main failures were observed as circumferential fractures.
- Nine of the ten samples revealed pH reduction or loss of alkalinity in the pipe wall due to soil side exposure.
- Failures were multi-stage, as below
  - First, pipe walls are weakened due to leaching of cement paste constituents.
  - Then failure occurs due to external vehicular loading. Improper pipe bedding could also contribute to pipe failure.
- Average wall thickness loss was 28.4 percent for the nine samples of various ages at the worst visually assessed areas. There was no correlation of wall loss to age.

- The lab results were consistent with Corrosion Probe's past findings for AC main failures and it indicates that when main wall integrity has been compromised at or greater than 30% of original section thickness, imminent localized failure of the pipe can be expected.

TOTAL PROJECT BUDGET BY TASK

The total project budget was approximately $ 2 million. The funding sources for the project was through General Obligation Bonds and Pay-as-you-go system. The total allocated budget is divided into tasks and is depicted in the Table 14 below.

Table 14: Total Project Budget by Task

Task	Labor Cost	Sub-contractor Cost	ODC Costs	Total Cost
Literature Review	$490	$14,950	$0	$15,440
Data Review and Validation	$19,540	$10,180	$0	$29,720
Preliminary AC Pipe Analysis/Cohorts & EUL	$3,760	$21,795	$0	$25,555
Water Distribution Service Level Review	$3,920	$0	$0	$3,920
Water Main Consequence of Failure GIS Data Review	$185,350	$0	$14,286	$199,636
Field and Laboratory Testing	$0	$0	$0	$0
Develop Field Plan and Procedures	$63,040	$11,615	$3,662	$78,317
Conduct AC Pipe Acoustical Testing	$41,030	$810,250	$610	$851,890
Perform AC Pipe Laboratory Analysis	$31,020	$92,920	$610	$124,550
Soil Sampling and Laboratory Analysis	$36,240	$149,000	$610	$185,850
Statistical	$39,350	$71,260	$5,312	

Failure Forecasting Modeling				$115,922
Master Planning Analysis - GIS RPT Config.	$99,290	$0	$5,312	$104,602
Draft and Final Master Plan Document	$77,790	$0	$122	$77,912
Transition Planning	$13,600	$10,180	$2,256	$26,036
Quality Assurance and Quality Control	$0	$50,050	$0	$50,050
Project Management	$57,350	$0	$1,830	$59,180
Additional Services	$50,000	$0	$0	$50,000
Total	**$721,770**	**$1,242,200**	**$34,610**	**$1,998,580**

KEY LESSONS LEARNED

- Acoustic testing was a lengthy process, which created problems in attaining traffic control plan permits.
- Over the course of this project, obtaining pipe samples was a difficult task, which resulted in some missing data.
- Also, a major difficulty was faced in obtaining pipe samples for laboratory testing due to lack of coordination in operations. This resulted in the samples being discarded in some instances.
- Extensive time is required in getting permits to conduct soil sample testing, which resulted in few delays
- One of the major concerns was the delayed start of the project.
- The change of project managers during project execution caused some delay. This delay is owed to the learning curve of the new managers.
- A pipe selection criterion was one of the issues in terms of selecting the pipe to test.
- Lack of knowledge on the field conditions is one of the challenge encountered. The access and impacts to the public was an issue in this scenario.
- Regular resolution meetings and follow up with the permitting department would reduce the delays in the project.

BIBLIOGRAPHY

Technical Memorandum: City of San Diego, Public Utilities Department Asbestos Cement Water Main Replacement Program Master Plan (H125808)

Technical Memorandum No. 2:City of San Diego, Asbestos Cement Water Main Replacement Program Master Plan Project Management Plan(H125808)

Technical Memorandum 3: City of San Diego, Asbestos Cement Water Main Replacement Program Master Plan(H125808)Consequence of Failure Analysis

Technical Memorandum 4: City of San Diego, Asbestos Cement Water Main Replacement Program Master Plan(H125808)Data Review and Validation

Technical Memorandum 5A: City of San Diego, Asbestos Cement Water Main Replacement Program Master Plan(H125808)Field Investigation Plan and Procedures(Phase 1)

Technical Memorandum 6A: City of San Diego, Asbestos Cement Water Main Replacement Program Master Plan(H125808)Acoustic Testing (Phase 1)

Technical Memorandum 8: City of San Diego, Asbestos Cement Water Main Replacement Program Master Plan(H125808)AC Main Samples Laboratory Analysis

Agreement Between the City of San Diego and Arcadis U.S., inc. for Asbestos Cement Water Main Replacement Program Master Plan(H125808)

SWIM Case Study Screening Level Questionnaire

SWIM Case Study Detailed Questionnaire - Pipe Condition Assessment