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Empirical Analysis of Water-Main Failure Consequences

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Abstract

Modern urban societies depend greatly on critical lifeline systems such as drinking water supply. Water supply systems in the United States comprise about one million mile length of interconnected pipelines that transport water from sources to consumption points with the support of treatment plants, pumping stations, storage tanks and valves. While depleting freshwater sources in some regions is an alarming concern, supply infrastructure woes exacerbate the problem of meeting supply reliability targets. Evidenced by the "D" or lower grade it has been receiving over the past few ASCE infrastructure report cards, the quality of water supply infrastructure has degraded to an extent where 240,000 water mains fail annually in the U.S. A majority of these failures result in significant economic, environmental and societal consequences. Pro-active rehabilitation of deteriorated infrastructure will avoid these unwarranted failure consequences. This paper employs empirical analysis of the economic, environmental and societal consequences of large-diameter water main failures to estimate their overall impact cost. Data on the impacts of 11 large-diameter water main failures has been gathered and synthesized. The results of this paper will aid in predicting the future water main failure consequences to enable risk-based, long-term capital improvement planning of water supply systems.

Keywords: water sustainability; water infrastructure failures; societal costs of infrastructure failures

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1. Introduction

Continuous functioning of water supply infrastructure is crucial for human survival, public health and economic prosperity. Water supply infrastructure is constituted by reservoirs, storage tanks, pumping stations, and transmission and distribution mains. A majority of drinking water infrastructure in the U.S. is nearing the end of its intended useful life, requiring huge investments for revival. Consequently, they are becoming increasingly vulnerable to failures that add up to about 240,000 in number annually [1]. Many of the one million mile pipeline segments were never inspected until a problem aroused or pipeline failed. Some of these main breaks result in catastrophic economic, environmental and societal consequences that begs to revisit our overall approach of dealing with the current water infrastructure crisis.

Preventing water main failures when possible or minimizing their consequences are among one of the primary challenges currently faced by water utilities across the United States. Pro-active rehabilitation of deteriorated infrastructure will avoid these unwarranted failure consequences. Unfortunately, there exists limited awareness of the overall failure consequences of water main breaks in order to undertake a more informed rehabilitation decision making. Consequently, the end goal of this study is to employ empirical modeling of the economic, environmental and societal consequences of large-diameter water-main failures in the life-cycle analysis context in order to prioritize pipeline rehabilitation. This paper introduces a model to assess the overall consequences of large-diameter water main breaks, and summarizes the preliminary analysis conducted on empirical data gathered from 11 different large diameter water main failure cases.

2. Consequences of Water Main Break Model (COWAMB)

A simple-to-use Microsoft Excel based model, COWAMB, is developed in this study to estimate the overall consequences of large diameter water main breaks. COWAMB model is inspired by a previously proposed Grand Central Model (GCM) which was found to be overwhelmingly extensive and complicated for estimating the water main break consequences [2]. COWAMB is a simplified adaptation of the GCM model with only few data values needed to be collected for each water main break case. There are several inherent assumptions made in the development and use of COWAMB model which are consistent with those made in the GCM model. Also, any costs associated with repairing roads and damaged vehicles as a result of water main breaks are not included in the COWAMB model in its current form. COWAMB model is made up of three modules: (a) Data input, (b) Impact assessment, and (c) Results.

2.1. Data Input Module

The data input module collects all the necessary data from the user regarding the water main break. Data required includes some basic information that is usually available such as pipeline location, material, diameter, operating pressure, outage and repair durations, and prevailing cost of water supply. Other optional information that can be entered in the data input module, if known to the user, includes distribution of different types of buildings and number of consumers affected by possible supply outage and water flooding, average vehicle delay time due to traffic detours, and number of health issues reported in the service area. It is to be noted that some of the optional data that is required for COWAMB model may not be readily available, even by a water utility operator. Consequently, typical ranges for different parameters are indicated adjacent to the data entry cells in the data input module. The user can take his or her best guess on the parametric values based on failure magnitude, failure location, and other known data.

2.2. Impact Assessment Module

The Impact Assessment module contains the formulations of various impacts due to water main breaks. Water main break impacts are quantified in the COWAMB model as a combination of six cost categories out of which the first two categories are classified as *Direct Costs* and last four as *Indirect Costs*. The six cost categories include: (1)

Lost product, (2) Repair and return to service, (3) Travel delay, (4) Supply outage and substitution, (5) Health risk, and (6) Property damage.

Lost Product: Cost of lost water is estimated based on geometry of the pipeline failure, operating pressure, and time taken by the utility operator to isolate the failed section of the pipe. If the area of the break is not known, cross sectional area of the pipe is considered as the broken area for calculating the flow through it using the orifice flow equation.

Repair and Return to Service: Repair cost of pipeline failure is estimated as the sum of costs incurred for purchase and transportation of material and equipment, worker salaries, fringe benefits, and other miscellaneous tools used in the repair process.

Travel Delay: Costs resulting from traffic delays/detours following the failure and during repair are quantified based on the estimated Average Annual Daily Trips (AADT), estimated proportion of trips per hour during disruption, hourly operational cost of a vehicle, passengers per vehicle and estimated detour time.

Supply Outage and Substitution: Upon determining the number of buildings and customers affected by water supply outage, this category quantifies the cost of water supply outage based on the estimated amount of water used and cost of an alternate potable source for each customer during the supply outage. Bottled water is considered as the alternate source of water in this study. Cost of bottled water varies with failure location and therefore needs to be entered by the user.

Health Risk: Cost of health risk is estimated in this study following the principles and assumptions of GCM model where cost is based on impact probability. Using statistical methods, probability of population effected due to water main failures is estimated using historical trends. Effected population is sub-categorized into low-risk and high-risk based on the magnitude of failure. Cost is calculated based on lost wages, doctor fees, and hospital charges associated with contaminant based illnesses.

Property Damage: Cost of physical damage caused to buildings in the vicinity due to the pipeline failure is estimated in this category. The extent of property damage is estimated based on the amount of water lost from the main break. For every 7,571 m^3 of water lost, 1% value of any building in the surrounding area is assumed to get damaged due to flooding. Data on the number and types of buildings affected due to flooding varies and entered appropriately in the data input module for any given water main break. Average property values are considered based on the locality of the failure.

2.3. Results Module

The results module summarizes the overall cost of consequences and presents a pie chart illustrating the percent distribution of the six cost categories considered in the impact assessment module.

3. Case Studies

The developed COWAMB model is used in this study to estimate the overall costs of 11 large diameter water main breaks, out of which eight have occurred in the last six years. Majority of the data required for estimating the overall costs of the 11 water main breaks is obtained either from published literature or media reports obtained through significant internet search. Some reasonable assumptions were made based on the suggested ranges in the COWAMB model. The 11 cases presented in this paper represent a reasonably diverse sample that entails pipe materials such as grey cast iron, steel, and prestressed concrete cylinder pipe (PCCP), and diameters ranging between 762 mm to 3048 mm. Specific details for each of the studied cases are presented in Table-1, while some additional commentary is provided in the following paragraphs.

CASE 1: 914mm Steel pipeline, Sunset Boulevard, Los Angeles, California: The rupture of this nearly 100-year old water main caused a 4.5 meter wide sinkhole. The discharge from the broken main was estimated to be $2,178m^3$/hr, resulting in $6,814m^3$ of lost water. Hundreds of cars and buildings on the University of California in Los Angeles campus were damaged due to the break and the resulting flooding. It has taken nearly six hours for repairing the broken pipeline. [3] [4]

CASE 2: 762 mm Steel pipeline, UCLA Campus, Los Angeles, California: It has taken about four hours to isolate the failed section of the pipeline for repair in this case. The discharge in the meantime has flooded athletic fields, underground garages that housed several cars, and various walkways on the University of California in Los Angeles campus. Flooding in the amount of 181,058 m^3 also caused significant damage to the nearby properties stranding hundreds of vehicles in the parking structures and historic Pauley Pavilion's court. Due to higher traffic density, it has taken longer time to repair damaged roads resulting in increased travel delay costs. [5]

CASE 3: 1524 mm PCCP pipeline, Connecticut Avenue in Chevy Chase, Maryland: The failure occurred on Chevy Chase Lake Drive leaving a 6 meter deep crater. The large amount of water discharged caused flooding that severely damaged a lot of properties around the failure location. Nearly 1.8 million residents remained without water for nearly 11 hours due to this break. The intersection of Connecticut Avenue and Chevy Chase Lake Drive was closed due to the break for about six days after which it was reopened for traffic. As a result, travel delay costs were greater in this case.[6]

CASE 4: 1372mm PCCP pipeline, Capital Heights, Maryland: Frozen water was observed on the roads near by an office park where this failure has occurred. As a result, all southbound lanes of Interstate 95 for approximately two mile long, between Ritchie Marlboro Road and Route 214, were closed for two days. Consequently, it resulted in significant traffic detours and greater travel delay costs.[7] [8]

CASE 5: 3048mm Steel pipeline, Metro West Tunnel, Boston, Massachusetts: This failure resulted in the suspension of water supply for a 9-hour period, affecting two million residents and nearly an estimated 1,500 commercial buildings. While travel delay costs were not significant, damages inflicted on the nearby properties were very high as nearly 10 million m^3 of water flooded the surroundings of the failure. Due to the significantly higher magnitude of flooding, costs of property damage and lost product accounted for more than 50% of the overall impact cost. [7] [9] [10]

CASE 6: 1830 mm PCCP pipeline, Dundalk, Maryland: This failure resulted in significant damage to nearby properties due to the pipeline's higher elevation. Although there were no injuries due to this main break, 100 homes were reported to be flooded, in addition to washing away of a part of the road, damaging cars, trapping some residents in their homes. Due to the flooding, a section of the Broening highway was closed for two to four weeks while repair work on the road and the failed pipeline continued. Cost of property damage was significant in this case due to the high magnitude of damage caused by flooding. [7] [11]

CASE 7: 1676 mm PCCP pipeline, Denver, Colorado: This main break caused a sinkhole that is 12.2 meter wide and 4.8 meter deep, shutting down all northbound lanes of I-25. Although no injuries resulted due to this break, it has taken longer time to repair it, and therefore resulted in significant travel delay costs. Due to the failure location being closer to the Interstate-25, great damage was caused to the highway which reportedly took 11 days to repair before it was reopened. Consequently, costs of travel delays and repair work were high. [7] [12] [13]

CASE 8: 1676 mm PCCP pipeline, Bethesda, Maryland: Damage to nearby residential communities was prevented due to their significantly higher ground elevation relative to the failed pipeline. It was reported that discharge from the broken main was at a rate of $34,000m^3$/hr and that it has taken about three hours to isolate the broken pipeline section for repair, and an additional four hours to re-pressurize the water system in the county. As many as 18 cars were reported to be trapped in the discharged water that was 3 to 4 feet high in some locations. Few customers also

reported water discoloration for 12 to 18 hours after the break is fixed and pipeline re-commissioned into service. Travel delay costs are estimated to be significant due to the blocking of River Road traffic. [7] [14]

CASE 9: 1066 mm PCCP pipeline, Fort Lauderdale, Florida: Surrounding properties were significantly damaged due to the large amounts of discharged water. This water main break caused a 7.6 meter wide sinkhole collapsing a portion of the roadway it is buried under. Nearly 200,000 residents were reported to have been without water for more than 3 hours. Since this break occurred on a Christmas Eve, it has taken longer time and cost to fix it, for the lack of adequate work force available. [7] [15]

CASE 10: 1220 mm cast iron pipeline, Manhattan, New York: This break occurred between 19th and 20th streets near Madison Square, resulting in the explosion of a nearby gas pipeline that created a 7.6 meter deep and 60.9 meter wide crater in the middle of the street. The water main break created a 10.6 meter wide sinkhole collapsing a portion of the 5th Avenue Street. It has also resulted in the loss of approximately 635,950m^3 of water over a span of 6.5 hours. Although no one got injured, it was reported that numerous business houses, apartments and other nearby properties got damaged due to flooding.[7] [16]

CASE 11: 2438 mm PCCP pipeline, Montgomery County, Alabama: Before the utility operator could isolate the failed section of the pipeline, over 264,980 m^{3}of water was reported to be lost from the main break, which was about the same amount of water distributed daily by the respective utility operator. Water flooding due to the break blocked a roadway due to which cost of travel delay was greater. [7]

Table 1. Impact related data for water main break cases

	Month/Year	Pipe Diameter (mm)	Lost Product (m^3)	Repair Time (hr)	Operating Pressure (psi)	Overall Impact Cost ($ Million)
CS#1	September/2014	914[3]	6,814[2]	6[4]	110*	3.3
CS#2	July/2014	762[5]	181,058[2]	238[2]	200[18]	36.1
CS#3	March/2013	1524[6]	227,125[6]	144[6]	120*	21.9
CS#4	January/2011	1372[7]	189,270[8]	17[8]	125[7]	16
CS#5	May/2010	3048[19]	10,031,341[20]	60[21]	150*	85.3
CS#6	September/2009	1830[7]	552,451[2]	24[11]	110[7]	12
CS#7	February/2008	1676[7]	7,571[12]	264[12]	110[7]	18.7
CS#8	December/2008	1676[7]	170,344[2]	96[14]	118.6[7]	11.4
CS#9	June/2003	1066[7]	150,390[2]	10[15]	110[7]	6.2
CS#10	January/1998	1220[7]	638,388[2]	10[16]	110[7]	16.1
CS#11	March/1996	2438[7]	283,906[22]	72[22]	115[7]	9.9

*assumed values

4. Results and Analysis

The estimated overall costs of 11 water main breaks is collectively analyzed to evaluate the significance of each cost category and identify factors that led to the observed differences among the 11 cases. Table-1 presents the overall impact costs for the 11 water main breaks considered in this study. It can be observed from Table-1 that the overall impact cost ranged from about $3.3 million in the case of the 36-inch steel pipeline failure to an estimated $85.3 million in the case of the 120-inch PCCP pipeline failure. Figure-1 illustrates the distribution of the mean percentages of the overall impacts among the six cost categories. It can be observed from Figure-1 that cost of health

impacts accounted the least with 4%, while the cost of repair and re-commissioning of the broken pipeline accounted the greatest with 27% of the overall cost of water main breaks. While it is interesting to collectively analyze the gathered data, it should be noted that the eleven water main break cases considered in this study had significant variance in the data with the standard deviation ranging from 3.6 to about 15 percentage points. For example, the cost of lost water accounted for nearly 40% of the overall impact cost in case#5 while the mean percentage for that category is 8% as can be seen from Figure-1. This was due to the larger pipeline diameter (3050mm) and longer time to isolate the failed section in case#5.

The other interesting aspect of analysis is the share of direct versus indirect cost of impacts. Direct cost is the cost borne by the concerned water utility, whereas indirect cost is the cost left to the society to bear in majority of the cases. Direct costs include the definitive loss in revenue due to the lost water (i.e. cost category #1) and the costs incurred in repairing the broken water pipelines (i.e. cost category #2). Figure-2 illustrates the share of direct versus indirect costs for the eleven cases presented in this paper. It is calculated that the share of direct costs of water main break impacts averaged over the 11 cases is about 34%, while the indirect cost share is 66%. In general, where individual property damages suffered due to the main break are significantly high, water utilities may provide certain compensation. Also in cases of longer repair times, water utilities may provide temporary service connections using ad-hoc arrangements. In such cases the percent share of indirect costs would be lower than the estimated 66%.
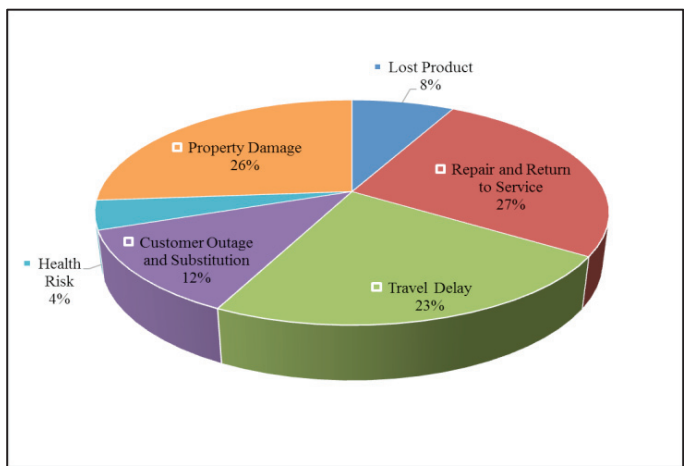

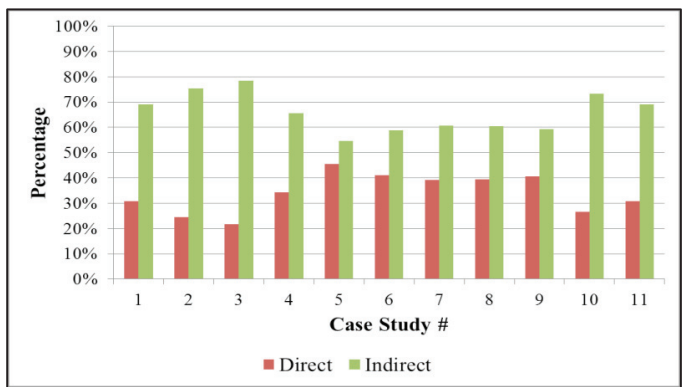Figure 1. Mean percentage distribution of overall costs

Figure 2. Percentage distribution of direct vs. indirect costs of water main breaks

5. Conclusions and Recommendations

A majority of buried water pipeline infrastructure is old and deteriorated needing to be replaced in the near future. Unfortunately, many municipalities lack the financial capabilities to invest in their infrastructure at a level that is required to overcome the deterioration menace. As a result, there are increasing numbers of water main failures across the United States among which some are proving to be catastrophic. Traditional water main rehabilitation planning involves failure risk assessment in which failure impacts were estimated in an overly simplified manner accounting only for the direct costs borne by water utilities. The objective of this paper is to present a model to estimate the overall impact cost of large diameter water main breaks. The presented COWAMB model, which is a simplified adaptation of a previously proposed grand central model (GCM), has been used to estimate the overall impact costs of 11 large diameter water main breaks that occurred in the US. COWAMB model estimated the costs of water main breaks by classifying them into six categories namely: lost product, repair and return to service, travel delays, supply outage, health risk, and property damage. The 11 cases considered included grey cast iron, steel and prestressed concrete cylinder pipeline materials, and diameters ranging from 760mm to 3050 mm.

The collective analysis of the 11 water main breaks revealed that health risk accounted for the least share, whereas repair and property damage accounted for the greatest share of the overall cost of impact. Results from 11 cases also revealed that direct costs which are definitely borne by the utility operator only constituted about 34%, while the indirect costs constituted the remaining 66% of the overall impact cost on an average. Some factors that were found to make a difference in overall impact costs included: (a) elevation of the pipeline relative to the surrounding communities and properties, (b) land use and traffic density in and around the failure location, (c) utility response time in identifying the exact failure location and isolating that section of the pipeline, (d) time taken to repair the failed pipeline, and (e) effective communication with consumers. Some recommendations to minimize the overall failure impact costs include: (1) less aggressive operating pressures in old main sections, (2) better monitoring capabilities of network performance to identify and locate failures as soon as they occur, (3) appropriate valve placements to be able to isolate smaller sections of failed pipelines, (4) adding network redundancy to be able to compensate for the loss of a critical asset during the time of repair, (5) preparedness with temporary water supply alternatives, and (6) preparedness for quicker failure repair times in the form of adequate training and properly maintaining necessary set of tools.

The results presented in this paper are based on only 11 case studies and therefore, drawing statistical trends was difficult especially because of larger variance observed in the output data. More case studies need to be prepared in the future to gather a more diverse database of water main break impacts for drawing more meaningful statistical trends and subsequent implications for water utility operators. Also, not all data required for estimating the overall impact costs is readily available at one place. Water utilities may be provided guidelines for collecting appropriate data as and when these water main breaks occur so that more confidence can be built into the results of the kind presented in this paper.

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