Examining Pipe Cost Changes After Various Disasters in Los Angeles, California

Sooin Kim, S.M.ASCE[1]; and Mohsen Shahandashti, M.ASCE[2]

[1]Graduate Research Assistant (corresponding author), Department of Civil Engineering, The University of Texas at Arlington. email: sooin.kim2@mavs.uta.edu

[2]Associate Professor, Department of Civil Engineering, The University of Texas at Arlington. email: mohsen@uta.edu

ABSTRACT

The rapid reconstruction of pipelines is crucial in the aftermath of a disaster since the pipeline networks transport and distribute life-dependent supplies such as water, natural gas, and electricity. However, the sudden post-disaster cost inflation often deters the timely reconstruction of pipelines. It is significant to investigate the pipe cost changes after different types of disasters to understand the threat of each disaster to pipeline networks. This research aims to examine the pipe cost changes after six various disasters in Los Angeles that California Governor proclaimed. The results show that the winter storm and floods had the most significant impacts on the magnitude and extent of post-disaster pipe cost changes, respectively. Although wildfire and COVID-19 are the costliest disasters in terms of financial expenditures, their impacts on pipe costs are smaller and more marginalized than those of other disasters. The research findings can assist pipeline engineers and cost estimators in enhancing their reconstruction cost management and plans.

INTRODUCTION

An increasing number of natural disasters pose an inevitable threat to communities (Susman et al. 2019). More than a hundred natural disasters affect the United States every year, causing numerous fatalities and billions of dollars of property and infrastructure damages (Boustan et al. 2020). With the rapid climate change, more severe meteorological disasters, including droughts, floods, wildfires, and earthquakes, have struck the U.S. regions, particularly California, in recent decades (Huang and Swain 2022). Sixty state emergencies and twenty federal major disasters have been declared per decade in California (The California Legislature's Nonpartisan Fiscal and Policy Advisor 2019). Los Angeles, one of the densely populated coastal regions in California, has experienced different disasters proclaimed by the California state governor.

Different types of disasters have different impacts on pipeline networks. Pipeline networks are required to be rapidly reconstructed and rehabilitated to serve the essential needs of people and accelerate disaster recovery in post-disaster situations (Kim and Shahandashti 2022a). Since unexpected cost inflation can hamper the reconstruction process, it is crucial to understand the pipe cost changes following different disasters for enhancing reconstruction plans and strategies (Kim et al. 2021b). Copper water tubing pipe cost increased by approximately 35 percent two months after Hurricane Katrina struck New Orleans in Louisiana (Khodahemmati and Shahandashti 2020). Polyvinyl-chloride sewer pipe and copper water tubing costs were inflated by 10 percent in Dallas two months after the 2021 Texas Winter Storm (Kim and Shahandashti 2022b). The skyrocketing lumber cost following the 2020 Oregon wildfire delayed housing reconstruction (Romero and Mann 2021). The lumber costs had tripled because of high post-wildfire demand coupled with supply shortages caused by the COVID-19 pandemic (Romero and Mann 2021). Supply chain disruptions by the COVID-19 pandemic inflated the overall construction material costs, including lumber, cement, and concrete products (Alsharef et al. 2021).

Despite the volume of studies on post-disaster construction cost changes, existing literature lacks the investigation of pipe cost changes following different disasters. It is crucial to examine how post-disaster pipe cost changes differ between disasters for preparing post-disaster pipe reconstruction and rehabilitation project strategies. This research aims to examine the Los Angeles pipe cost changes after six different disasters that California Governor proclaimed in the recent decade: the 2014 Drought, the 2015 Aliso Canyon natural gas leak, the 2017 California Floods, the 2018 Camp Creek Wildfire, 2019 Winter storm, and 2020 COVID-19 pandemic.

RESEARCH METHODS

Data Collection. City-level construction material costs monthly published by Engineering News-Record (ENR) are often utilized for preparing bid and budget proposals in construction and infrastructure projects (Kim et al. 2022). Table 1 summarizes the ENR pipe items in Los Angeles (LA) whose costs from January 2009 to December 2021 were collected.

Table 1. LA Pipe Items

Material	Line items
Reinforced concrete pipe	12”, 24”, 36”, 48”
Corrugated steel pipe	12”, 36”, 60”
Polyvinyl-chloride pipe (PVC): sewer	4”, 8”
Polyvinyl-chloride pipe (PVC): water	6”, 8”, 12”
Polyethylene pipe (PE): underdrain	4”
Ductile-iron pipe (DIP)	6”, 8”, 12”
Copper water tubing: type L	1/2”, 1 1/2”

The LA pipe cost changes were examined before and after disasters in Los Angeles that were proclaimed by California Governor. Table 2 shows six disasters in Los Angeles in the recent decade and training and testing datasets of pipe costs before and after disasters.

Table 2. California Governor-Proclaimed Disasters in Los Angeles

Date	Type of Disaster	Training dataset (Pre-disaster)	Testing dataset (Post-disaster)
Jan-14	Drought	Jan 09 – Dec 13	Jan 14 – Dec 14
Oct-15	Aliso Canyon natural gas leak	Jan 09 – Sep 15	Oct 15 – Nov 16
Jan-17	Storm System (Floods)	Jan 09 – Dec 16	Jan 17 – Dec 18
Nov-18	Camp Creek Wildfire	Jan 09 – Oct 18	Nov 18 – Oct 19
Jan-19	Winter Storm	Jan 09 – Dec 18	Jan 19 – Dec 19
Mar-20	COVID-19 pandemic	Jan 09 – Feb 20	Mar 20 – Feb 21

Time Series Characteristics Analysis. Since the autocorrelations among the LA pipe cost time series can provide a false signal about major cost changes in Cumulative Sum (CUSUM) control charts, it is important to investigate the existence of autocorrelations among the pipe costs that are subject to fluctuations over time (Kim et al. 2021a). The Ljung-Box Q-test was used to check for autocorrelations between the pipe costs. The stationarity and seasonality of the LA pipe costs were identified using the Augmented Dickey-Fuller (ADF) test and time-series decomposition, respectively (Kim et al. 2022).

Time Series Model Development. According to the results of the time-series analyses, the appropriate time-series models were developed to fit the LA pipe costs. Seasonal Autoregressive Integrated Moving Average (SARIMA) is commonly used to model the time series with nonstationarity and seasonality (Kim et al. 2020). The Ljung-Box statistics were used for the developed SARIMA model diagnoses.

CUSUM Control Chart Illustration. Unexpected out-of-control changes can be statistically diagnosed using CUSUM control charts (Kim et al. 2022). The out-of-control points are the points plotted over the upper control limit or below the lower control limit in the CUSUM control chart. The recovery period starts from the deviation of the out-of-control points and ends with the return of the out-of-control points to the normal process.

Cost Change Quantification. The LA pipe cost forecasts of the SARIMA models capturing the normal variations of pipe costs were compared with the observed pipe costs during the recovery period to examine the disaster impacts on the cost variations.

EMPIRICAL RESULTS

The Results of Time-Series Analysis. Autocorrelations were found among the historical LA pipe costs based on the Ljung-Box Q-test results. The null hypotheses of no autocorrelation were rejected at the 1% significance level for all LA pipe costs. The results of the Ljung-Box Q-test signify that time-series models need to be developed to capture and approximate the autocorrelations among the historical LA pipe cost data. According to the results of the ADF tests, the LA pipe costs were found stationary because the null hypothesis of nonstationarity was rejected at the 1% significance level. According to the results of decomposition, all LA pipe costs also revealed a twelve-month seasonality. SARIMA models were developed based on the results of time-series analysis since all LA pipe costs are nonstationary and seasonal over time. The SARIMA model was developed using the training dataset in Table 2 for each disaster and selected based on the Akaike Information Criterion (AIC).

The Results of Major Cost Change Detection in CUSUM Control Charts. Figures 1 and 2 illustrate the major reinforced concrete pipe cost changes in CUSUM control charts after the 2019 California Winter Storm. The cost deviation started in March 2017, two months after the 2019 California Winter Storm, and ended in December 2017. The first out-of-control point in the forward CUSUM control chart was observed in October 2017, while the first out-of-control point in the reverse CUSUM control chart was observed in May 2017. The quadrupled standard deviations were used as the upper and lower control limits to detect out-of-control cost changes.

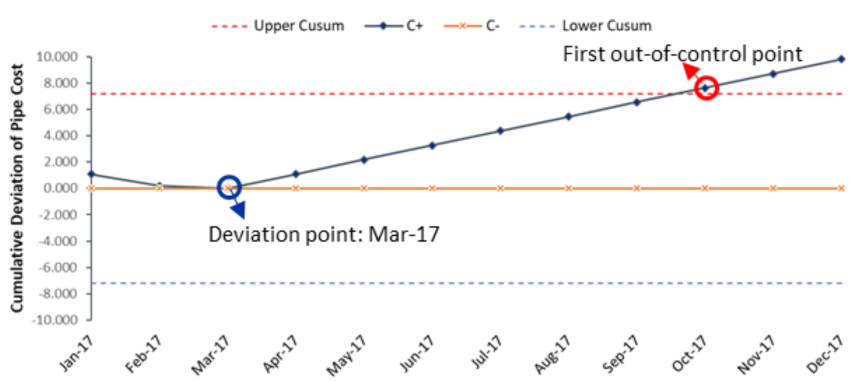

Figure 1. Forward CUSUM Charts for Reinforced Concrete Pipe Costs

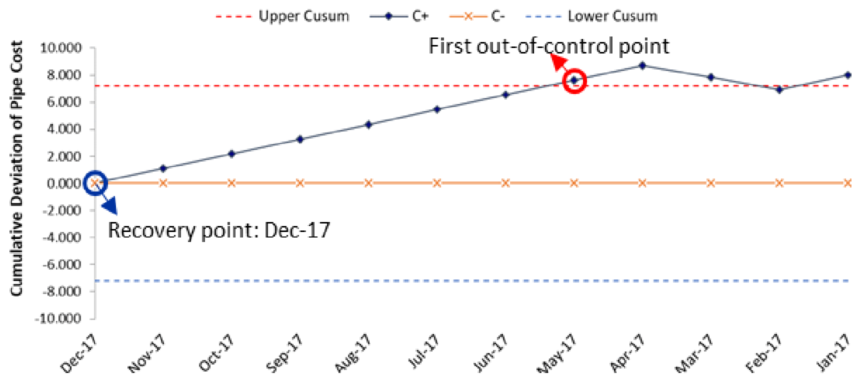

Figure 2. Reverse CUSUM Charts for Reinforced Concrete Pipe Costs

Cost Change Quantification Results.

Los Angeles Pipe Cost Changes after 2014 Drought. According to the out-of-control point diagnoses, no major change was found in LA pipe costs after the 2014 Drought. These results seem plausible because the influence of drought on pipe failures is relatively small compared to other disasters' influences (Wols et al. 2019). Major cost changes in LA pipes were reported after the 2015 Aliso Canyon Natural Gas Leak, 2017 California Floods, 2018 Camp Creek Wildfire, and 2019 Winter storm as described in Tables 3 to 6.

Los Angeles Pipe Cost Changes after 2015 Aliso Canyon Natural Gas Leak. Reinforced concrete pipe costs, corrugate steel pipe costs, and ductile-iron pipe costs have increased after the 2015 Aliso Canyon Natural Gas Leak based on the results of out-of-point diagnoses in Table 3.

Table 3. Major Cost Changes for LA Pipes after 2015 Natural Gas Leak

Pipe material cost	Recovery period	Average cost (Observed, $/ft)	Average cost (Forecasted, $/ft)	Change (%)
Reinforced concrete pipe 12”	Jan 16-Sep 16	14.34	12.39	15.70%
Reinforced concrete pipe 24”	Jan 16-Sep 16	27.33	25.26	8.20%
Reinforced concrete pipe 36”	Jan 16-Sep 16	56.44	51.38	9.80%
Corrugated steel pipe 12”	Dec 15-Sep 16	9.34	8.2	13.90%
Corrugated steel pipe 36”	Jan 16-Sep 16	28.3	25.69	10.20%
Ductile-iron pipe (DIP) 6”	Jan 16-Sep 16	14.78	12.82	15.30%
Ductile-iron pipe (DIP) 8”	Jan 16-Sep 16	22.67	19.05	19.00%
Ductile-iron pipe (DIP) 12”	Jan 16-Sep 16	35.44	30.13	17.60%

This is perhaps because these reinforced concrete pipes, corrugated steel pipes, and ductile-iron pipes were subject to high demand after the 2017 Aliso Canyon Natural Gas Leak disaster. The rupture of highly pressurized corroded pipes in natural gas distribution systems owned by SoCalGas caused the massive gas leak in Aliso Canyon near Los Angeles on October 23rd, 2015 (California Public Utilities Commission (CPUC) 2019). Investigators found the gas leak started at the base of the porous concrete pipes and encasements (Peterson 2016). Deteriorating cast iron pipes in the natural gas distribution systems of SoCalGas were also required to be replaced (California Public Utilities Commission 2020). Furthermore, SoCalGas installed more than 40 miles of steel pipe into old wells according to the results of a state safety review (Bartholomew 2016; US Forest Service 2022).

Los Angeles Pipe Cost Changes after 2017 California Floods. Reinforced concrete pipes, corrugated steel pipes, Polyvinyl-chloride (PVC) water pipes, Polyethylene (PE) underdrain pipes, and ductile-iron pipes have experienced major cost escalations after the 2017 California Floods, as shown in Table 4.

Table 4. Major Cost Changes for LA Pipes after 2017 California Floods

Pipe material cost	**Recovery period**	**Average cost (Observed, $/ft)**	**Average cost (Forecasted, $/ft)**	**Change (%)**
Reinforced concrete pipe 12”	Mar 17-Dec 17	16.29	14.5	12.30%
Reinforced concrete pipe 24”	Mar 17-Dec 17	34.29	27.5	24.70%
Reinforced concrete pipe 36”	Mar 17-Dec 17	74.55	57	30.80%
Reinforced concrete pipe 48”	Mar 17-Dec 17	122.38	92	33.00%
Corrugated steel pipe 36”	Mar 17-Dec 17	31.88	28.5	11.90%
Corrugated steel pipe 60”	Mar 17-Dec 17	74.12	68	9.00%
Polyvinyl-chloride pipe (PVC): water 12”	Mar 17-Dec 17	21.31	17.5	21.80%
Polyethylene pipe (PE): underdrain 4”	Mar 17-Dec 17	1.11	1	11.00%
Ductile-iron pipe (DIP) 6”	Mar 17-Dec 17	18.71	15	24.70%
Ductile-iron pipe (DIP) 8”	Mar 17-Dec 17	30.09	23	30.80%
Ductile-iron pipe (DIP) 12”	Mar 17-Dec 17	41.28	36	14.70%

Those reinforced concrete pipes, corrugated steel pipes, and ductile-iron pipes are subject to flood risks due to their material corrosion (Camp 2020; Folkman 2014). Reinforced concrete pipes that are widely used for sewer infrastructure systems often suffer from a critical deterioration process due to concrete and rebar corrosion (Song et al. 2020). Steel pipelines are also likely to undergo corrosion on exposure to water (Darwin et al. 2010). Iron water pipe networks experience external and internal corrosion under time-dependent deterioration and flooding disruptions (Mahmoodian and Li 2016). The corrosive material properties of reinforced concrete, steel, and ductile iron in pipelines can increase the risks of pipeline failures and subsequently escalate the pipeline reconstruction and rehabilitation demand, inflating the pipe costs after 2017 California Floods.

Unlike traditional metal pipes, PVC and PE pipes are resistant to corrosion (Barton et al. 2019). Because of the noncorrosive material properties, PVC water and PE underdrain pipes are installed for stormwater infiltration systems for flood prevention (Petit-Boix et al. 2015). The PVC water and PE underdrain pipes experience an increasing demand to drain excess water after floods and storms (Arocho-Irizarry et al. 2018). This increasing demand for the PVC water pipe and PE underdrain pipe probably causes their cost inflation of over 10 percent following the 2017 California Floods.

Los Angeles Pipe Cost Changes after 2018 Camp Creek Wildfire. The 2018 Camp Fire was initiated by electrical transmission lines improperly managed by Pacific Gas and Electric (Daniels 2019). Table 5 shows the cost inflation of corrugated steel pipes and Polyethylene (PE) pipes and the cost deflation of Polyvinyl-chloride pipe (PVC) water pipe after the 2018 Camp Creek Wildfire.

Table 5. Major Cost Changes for LA Pipes after 2018 Camp Creek Wildfire

Pipe material cost	Recovery period	Average cost (Observed, $/ft)	Average cost (Forecasted, $/ft)	Change (%)
Corrugated steel pipe 36”	Apr 19-Oct 19	37.04	32.26	14.8%
Corrugated steel pipe 60”	Jul 19-Oct 19	83.45	74.8	11.6%
Polyvinyl-chloride pipe (PVC): water 6”	Apr 19-Oct 19	7.19	9.15	-21.4%
Polyethylene pipe (PE): underdrain 4”	May 19-Oct 19	1.37	1.12	22.3%

The California underground infrastructures, including thermoplastic and corrugated metal systems, were damaged and destroyed by the 2018 wildfires in California (Tripp 2018). PVC and PE pipes are not inherently fire resistant, having a lower melting temperature than other metal or concrete pipes (Richter et al. 2022; Swanger 2019). States’ Departments of Transportation (DOTs), including Colorado DOT, Iowa DOT, South Dakota DOT, and North Dakota DOT, have already reported substantial fire risks and flammability of polyethylene pipes (Swanger 2019). Despite the fire-retardant pipe coatings, the sustained fire such as the 2018 Camp Creek Wildfire in California can ultimately transfer the heat to the PE pipes below the coatings, which could cause structural damage, melting, or even combustion of the PE pipes (Swanger 2019). PVC and PE pipes are widely used for water distribution and building plumbing systems due to their flexibility and low cost (Isaacson et al. 2021). PVC pipe is a low-cost material option for pressurized or suspended systems but inappropriate for extreme temperature fluctuations (Oriplast 2021). On the other hand, PE pipe is more appropriate than PVC pipe for drinking water infrastructure systems that can be exposed to extreme temperatures (Oriplast 2021). The 2018 Camp Creek Wildfire affected 35 percent of plastic water pipe systems and caused water contamination (Isaacson et al. 2021). The Environmental Protection Agency (EPA) estimated that plastic pipes damaged by the 2018 Camp Creek Wildfire required more than 100 days of water rinsing for safe reuse (Whelton et al. 2020). Instead, the California local irrigation department replaced all water service lines using new PE pipes (Cooper 2021). Insurance companies encouraged property owners and city officials to install fire-resistant metal pipes instead of plastic pipes (Whelton et al. 2020). This can be a possible reason for corrugated steel and PE pipes cost inflation by the increasing demand for those pipes and PVC pipe cost deflation by the decreasing demand for PVC pipes in the aftermath of the 2018 Camp Creek Wildfire in California.

Los Angeles Pipe Cost Changes after 2019 Winter Storm. Table 6 shows the major cost inflation of reinforced concrete pipe, Polyvinyl-chloride (PVC) sewer pipe, and Polyethylene (PE) underdrain pipe after the 2019 Winter storm in California. Reinforced concrete pipes are exposed to inherent stress, potential cracking, and spalling during seasonal weather conditions of vicious freeze-thaw cycles (Whittaker 2019). The severe freeze-thaw cycles following the 2019 Winter Storm in California probably increased the failures of reinforced concrete pipes, leading to the rise in the reinforced concrete pipe demand and costs. The major cost inflation of PVC sewer pipe in the aftermath of the 2019 California Winter Storm aligns with the findings of previous research about the pipe cost changes after the 2021 Texas Winter Storm (Kim and Shahandashti 2022b). The Dallas PVC sewer pipe experienced a major cost increase when the 2021 Texas Winter Storm hit the Dallas area (Kim and Shahandashti 2022b). The PVC sewer pipe and PE underdrain pipe possibly burst or broke in the freezing weather of the 2019 California Winter Storm due to the water expansion (Barton et al. 2020; Zhang and Kevern 2021). a***le 6. Major Cost Changes for LA Pipes after 2019 Winter Storm***

Pipe material cost	Recovery period	Average cost (Observed, $/ft)	Average cost (Forecasted, $/ft)	Change (%)
Reinforced concrete pipe 12”	Oct 19 – Dec 19	23.73	16.49	43.89%
Polyvinyl-chloride pipe (PVC): sewer 4”	Sep 19 – Dec 19	1.95	1.5	30.00%
Polyethylene pipe (PE): underdrain 4”	Jul 19 – Dec 19	1.3	1.12	15.63%

Los Angeles Pipe Cost Changes after 2020 COVID-19 Pandemic. The results of out-of-control point diagnoses found no major LA pipe cost changes after the 2020 COVID-19 pandemic. It is unlikely to find the COVID-19 pandemic's impact on pipe failures or regional pipe costs because the COVID-19 pandemic is a public health emergency and disaster (Peleg et al. 2021). While the prices of building materials such as lumber skyrocketed with an increasing demand for home renovations during the COVID-19 pandemic (Bousquin 2021; Hudd 2021; Kim, Makhmalbaf, et al. 2022; Pelchen and Allen 2022), the pipe prices had not experienced major cost inflation due to the decreasing demand for pipes following obstructions and cancellations of pipeline infrastructure projects in the aftermath of the 2020 COVID-19 pandemic situations (Awalt 2020; Pipelines for America 2020).

CONCLUSIONS

The current research investigated the post-disaster LA pipe cost changes in the aftermath of six different disasters in California using CUSUM control charts and SARIMA models. The results identify the vulnerable pipes to each disaster whose costs had statistically significantly inflated following the disaster. The winter storm and floods had the greatest impacts on the magnitude and extent of post-disaster pipe cost changes, respectively. Reinforced concrete pipe costs increased over 40% and 30% following the 2019 Winter Storm and the 2017 California floods, respectively. The reinforced concrete pipes were vulnerable to severe freeze-thaw cycles during the winter storm. Also, the reinforced concrete pipes widely used for sewer infrastructure systems seemed to suffer from a critical deterioration process due to concrete and rebar corrosion following the 2017 floods. Although wildfire and COVID-19 are costlier than the other disasters in terms of financial expenditures, their impacts on pipe costs are smaller and more marginalized than those of other disasters. Also, the same type of pipe is likely to show a similar recovery period and cost fluctuations following a disaster, regardless of its different sizes. It is expected that the research findings can assist pipeline engineers and cost planners in identifying the post-disaster pipe cost changes following various disasters for enhancing their reconstruction cost management and strategies and executing a timely reconstruction process.

Despite the useful findings, this research is subject to a few limitations. First, the scale or cost of disasters was not considered in examining the post-disaster pipe cost changes. Also, other influencing factors, such as the spatial proximity of pipeline locations to the disaster-stricken areas, were not included in the pipe cost change examination. Future research can stretch the framework of the current research and further investigate the post-disaster pipe cost variations using other influencing factors such as the scale of disasters and spatial proximity and other regional costs or indices in different disaster scenarios.

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