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Econometric Analysis and Cost Forecasting for Relining Large Pipes

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This research used econometric techniques to evaluate 73 relining jobs for large diameter steel pipe interiors to identify major cost drivers for such relining jobs and to specify a regression model for predicting future relining job costs. Reclamation's inventory of 121 unrelined penstocks was evaluated with the final model to predict preliminary-level costs for future relining work. An app tool was developed using Microsoft Power Apps as an end-user interface for predicting relining costs based on the final regression model. A subsequent Microsoft Excel tool was developed to share with the study's contribution partner agencies: Metropolitan Water District, Central Arizona Project, Denver Water, and BC Hydro.

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Cover photo credit: Grand Coulee Left Powerplant Unit G8 Penstock Relining.

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Econometric Analysis and Cost Forecasting for Relining Large Pipes

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Acronyms and Abbreviations

$M	Millions of dollars
2020$	Dollar value reported at a 2020 price level
App tool	Application-based tool
ASCE	American Society of Civil Engineers
ATC	Average total cost
AW	Area-weighted
CAP	Central Arizona Project
CCT	Reclamation's Construction Cost Trends index
CGB	DOI's California-Great Basin Region
CLIN	Contract line item number
CMAR	Construction manager at risk
CPN	DOI's Columbia-Pacific Northwest Region
CTE	Coal tar enamel
DB	Design-build
DBB	Design, bid, build
Deg	Degree
DOI	United States Department of the Interior
EUAC	Equivalent uniform annual cost
FY2021 Planning Rate	Fiscal Year 2021 interest rate in the formulation and evaluation of plans for water and related land resources
Ft	Feet
GMP	Guaranteed maximum price
IDIQ	Indefinite date, indefinite quantity
IGCE	Independent government cost estimate
JOC	Job order contract
LC	DOI's Lower Colorado Basin Region
LCC	Lifecycle cost analysis
Ln	Natural log
LW	Length-weighted
MBA	DOI's Missouri Basin and Arkansas-Rio Grande-Texas Gulf Regions

MEPD	Reclamation's Mechanical Equipment Penstock Database
MSL	Feet above mean sea level
MWD	Metropolitan Water District
NBS-BCL	National Bureau of Standards – Battelle Columbus Laboratories
NIST	National Institute for Standards and Technology
NPV	Net present value
PDM	Project delivery method
POMTS	Power Operations and Maintenance Tracking System
PRO	Power Resources Office
Q	Quantity (area relined)
Q&A	Question and answer
QBS	Quality-based selection
Reclamation	Bureau of Reclamation
RFP	Request for proposals
RMSE	Root-mean-squared error
S&T	Science and Technology
SEs	Standard errors
SF	Standard form
sqft	Square foot (or feet)
TC	Total cost
TSC	Reclamation Technical Service Center
UC	DOI's Upper Colorado Basin Region
UW	Unweighted
Z	Other factors

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Executive Summary

This research used econometric techniques to evaluate large diameter steel pipe interior relining jobs contracted by the Bureau of Reclamation (Reclamation) and participating partner agencies. For the purposes of this study, large diameter is defined as 42 inches and larger. The primary research objectives were to (1) identify major cost drivers for these relining jobs, and (2) develop a regression model for predicting future relining job costs.

The standard practice at Reclamation is to reline large steel pipes, e.g., penstocks and outlet pipes, in its inventory to replace degraded protective coatings. Relining ensures corrosion protection is optimized and the corrosion of the underlying steel pipe is minimized. The average age for Reclamation's 188 penstocks is 70 years, which is approaching the expected lining service life on most structures. The analysis performed here results in tools to predict future large diameter steel pipe relining costs and provide guidance for future budgeting decisions.

The data collection and aggregation phase resulted in the development of 73 observations from multiple large steel pipe relining job award contracts from four water management agencies. Each of the 73 observations include award contract costs, i.e., the cost commitment at the time the contract is enacted. Final contract costs were available for only 16 of the 73 relining jobs evaluated, as many of the jobs are in progress. The final contract cost includes contract modifications that occur during project execution and generally result in cost increases or decreases. The sources utilized during development of the 73 observations included relining job contract specifications, drawings, and schedule of values, the Technical Service Center Mechanical Equipment Database and Cost Estimating Expect Database, and informal summaries via personal communication.

Observations consisted of two sets of variables for analysis—relining job data and physical feature data. Relining job data are related to a specific large pipe relining job, such as square feet (sqft) of area relined, awarded contract cost, contract award year, whether robotic coating removal and application were used, etc. By contrast the physical feature data are constant and inherent to the facility, with examples being facility name and type, ownership, pipe length, diameter, and slope, etc.

Regression analysis was used to test the variables identified as potential cost drivers for relining contracts, identifying statistically significant trends and relationships between variables and their impact on cost. The analysis found the following preliminary conclusions.

- Quantity relined is found to be the main driver of total relining cost and a main driver of unit cost (cost per sqft) due to strong economies of scale (decreasing unit cost with increasing quantity relined).
- Pipe diameter has a varying effect on application cost of manual versus robotics—increasing diameter appears to increase robotics cost, while manual application cost is higher for a smaller diameter.
- Pipe slope has a varying effect on application cost of manual versus robotics—slope has a smaller effect on the cost of robotic application, becoming similar in cost at very steep slopes, all else equal, while manual application is cheaper when pipe slope is low but becomes more expensive as slope increases.

- The model indicates that cost is on average higher in the LC Region, followed by (in order of decreasing cost) the CGB, UC, MBA, and CPN regions.
- When controlling for other factors, Reclamation pays approximately 72 percent more per sqft relined than non-Reclamation entities ($79 per sqft versus $46 per sqft, respectively).

The final regression model was used to predict relining costs for the 121 Reclamation steel penstocks not in the study sample, i.e., those that are likely to be relined in the near future, using two approaches: lump sum and sequential. The lump sum approach assumes all penstocks are relined in the current year, resulting in an undiscounted cost and simplified calculation. By this approach, the cost to Reclamation for relining the 4.8 million sqft of steel penstock evaluated is $228 million (2020 price level). The sequential approach, by contrast, assumes that the timing of future relining is one penstock per region per year. This approach attempts to account for the reality that penstock relining jobs compete for many of the same resources as other Reclamation construction projects. Further, it discounts the cost of future relining work to its present value. The result is a total cost for relining the 121 penstocks evaluated of $168 million in present dollars, or an equivalent uniform annualized cost (EUAC) of $6.9 million—the economic cost Reclamation might expect for penstock relining jobs per year.

A final research outcome is an application-based tool (app tool) to serve as an interface for end users to predict costs based on the results of the final regression model. The app tool was built in Microsoft Power Apps and requires the user to input the cost-driving variables: area relined, pipe diameter and slope, whether it is a Reclamation contract, whether the contractor will use robotics, and the Reclamation region where the work is located. The output is the predicted cost reported at a 2020 price level as total cost and as cost per sqft—both given with 95 percent confidence intervals. The same tool is developed as a Microsoft Excel spreadsheet for use outside the Department of Interior, including research partners.

Next steps identified for this research are as follows:

- Update the observation dataset and regression model as data become available.
- Perform out-of-sample model truthing once additional award data become available.
- Develop a model comparing award versus final contract data once they become available.
- Expand sample size to increase proportion of non-Reclamation agencies to explore and better explain the observed interagency difference in relining unit cost.
- Investigate in detail the cost-effectiveness of robotics usage for relining jobs.
- Determine the break-even point at which relining is more cost effective than spot repair.
- Evaluate the effect of physical access to the pipe such as manhole locations and hose length.
- Perform a benefit-cost analysis of not relining penstocks, i.e., run-to-failure.

1 Introduction

The Bureau of Reclamation (Reclamation) operates and maintains 188 hydroelectric power penstocks and an unquantified number of additional large and small diameter steel pipes, such as storage reservoir outlet pipes. The 188 penstocks alone comprise a combined 6.6 million square feet (sqft) of interior surface area. The steel surface requires protective coatings to prevent corrosion damage, e.g., metal loss by wall thinning and pitting, which lead to expensive weld repairs or section replacements. Corrosion damage reduces the reliability of water delivery and power generation and can result in pipe rupture or decommissioning.

The periodic costs associated with spot repairing or removing and replacing protective coatings, i.e., coatings and linings, are part of operation and maintenance budgets for the facility. In some cases, end users, such as water and power customers, fund this maintenance. Recent experience suggests an upward trend in the frequency and cost of this maintenance, indicating that future budget needs may be rising. Better understanding these cost trends and improving the available cost estimating tools will aid budgeting, project planning, and communication.

This research employs econometric analysis of pipe physical features and contract data to investigate cost drivers associated with interior lining maintenance (i.e., relining jobs) for large diameter steel pipes (42-inch diameter and larger). Econometrics is the application of statistical methods to economic data and allows for the evaluation of datasets to identify statistically significant variables, relationships, and trends. Understanding the cost drivers for these relining jobs improves budgeting and exposes opportunities to increase efficiencies. The research follows this four-step strategy:

1. Data aggregation from large diameter pipe relining contracts and pipe physical features, organized as potential variables.
2. Econometric analysis to identify statistically significant trends and relationships between relining costs, relining job specifications, and pipe physical features.
3. Specification of a final regression model that estimates large diameter pipe relining cost as a function of select explanatory variables.
4. Truthing of the final regression model against out-of-sample data, including historical or currently awarded relining jobs.

Developing a robust approach and aggregating a large dataset for this analysis required a multi-disciplinary team and industry partners. The Reclamation research team included protective coatings and corrosion specialists, economists, and cost estimators. The research partners included construction managers, contract specialists, and coating contract managers from Reclamation, Central Arizona Project, BC Hydro, Metropolitan Water District, and Denver Water.

1.1 Economic Considerations

The terms "cost" and "price" are used in this study. In general, cost indicates the expense incurred for creating a good or service, while price is the amount a customer is willing to pay for that good or service. Applying this convention, price is the amount faced by water management agencies to procure a relining contract, which includes the contractor's costs plus their mark-ups (overhead and profits). However, this convention is by no means a hard and fast rule. For consistency and simplification, this study applies the term "cost" to the relining jobs evaluated for econometric analysis (i.e., the *cost* faced by the agency), while reserving the term "price" for the cost estimating and economic price level discussions.

The study sample includes data from relining contracts awarded from 1999 through 2020. Objective comparison of costs requires that they be adjusted to a common price level. All costs are indexed to "real" 2020 dollars[1] using Reclamation's *Construction Cost Trends* index (CCT) for steel pipelines (Reclamation, 2021a). The shorthand "2020$" is used in some instances hereafter, denoting dollars reported at a 2020 price level. All costs are reported at a 2020 price level unless otherwise stated.

In the consideration of cost predictions, all future relining costs are discounted to their present value using the interest rate prescribed for Federal agencies in the formulation and evaluation of plans for water and related land resources for Fiscal Year 2021 (FY2021 Planning Rate) of 2.500 percent (Federal Register, 2020) to account for the time value of money. The FY2021 Planning Rate is employed as a real discount rate and Reclamation economic analyses therefore report results in real dollars (i.e., there is no assumption of inflation). Standard Reclamation cost estimating practices estimate inflation by escalating costs to a future price level to include two distinct periods of time: the period from estimate preparation until Notice to Proceed, and the period equal to the duration of the construction contract. This study does not apply cost estimating standards or practices and should not be construed as such.

2 Background

Conventional wisdom indicates the unit cost for contemporary large pipe lining maintenance contracts is on the order of \$30–\$100 (2020$) per sqft for a full relining of typical-sized penstocks. Spot repairs on the same penstock may be an order of magnitude higher unit cost than the full relining unit cost, all else equal. Spot repair costs are generally higher unit cost due to the inefficiencies involved in moving the work staging area from spot-to-spot. Further the contractor's fixed costs for traveling to and preparing the job site for safe work inside the penstock are spread across a smaller volume of work for spot repair projects.

Reclamation's *Mechanical Equipment Penstock Database* (MEPD) catalogues each penstock in its inventory for length, diameter, surface area, etc. The MEPD shows that agency-wide Reclamation

[1] A "real dollar" value is an adjusted value that attempts to account for the impacts of inflation—the change in the purchasing power of a dollar. A real dollar value is used in this analysis to allow for better comparability of resource values across time. The estimated purchasing power of a dollar in year 2020 is used as the base value of a dollar (reference year).

maintains 188 penstocks constituting a total internal surface area of 6,582,665 sqft. Figure 2-1 shows Reclamation's total number of penstocks and total penstock interior surface area by Reclamation region.

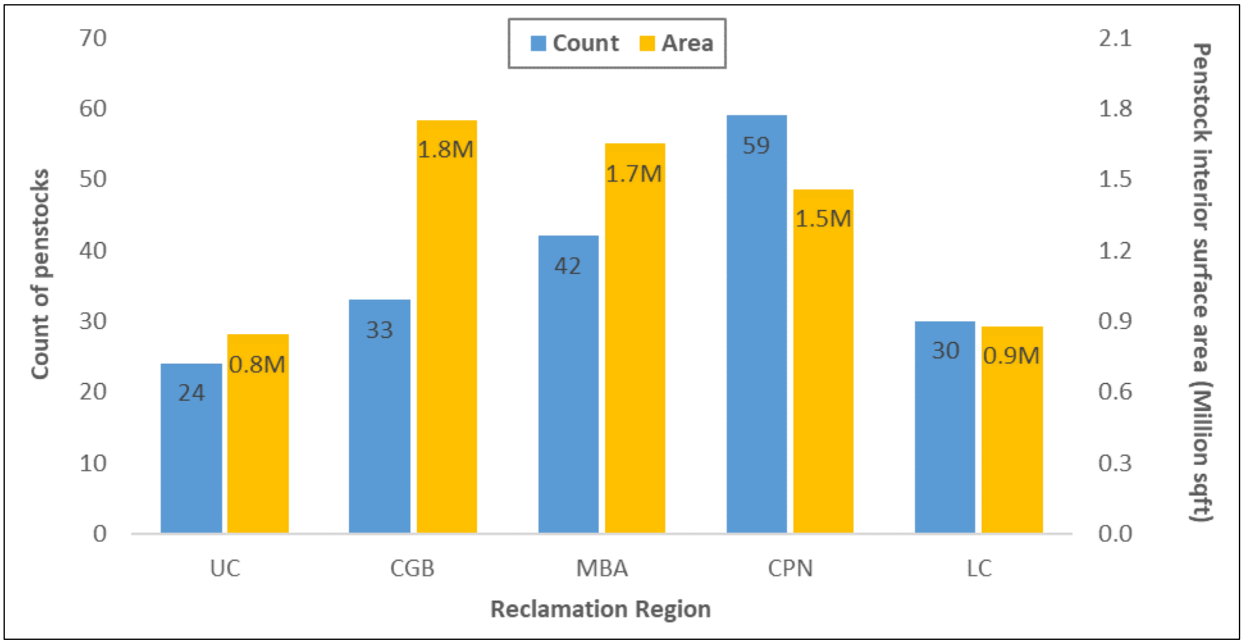


Figure 2-1. Reclamation penstock count and total interior surface area by region

Penstock relining jobs often include the relining of appurtenant features as well. These appurtenances can be large pipe features, such as outlet tubes, or more complex features, such as draft tubes and scroll cases. Beyond penstocks, Reclamation also manages other large diameter and small diameter steel pipes that require lining maintenance, such as storage reservoir outlet pipes, which are not reported in the MEPD. The area estimates provided in Figure 2-1 are exclusive to penstocks, so are necessarily an underestimate of the steel surface area that Reclamation maintains with linings.

Each penstock requires a scheduled unit outage, typically for several months, for a full relining. The study does not capture the opportunity costs associated with the lost hydropower production due to the unit outage. There is sometimes little or no impact resulting from the lost hydropower production, and in other cases it is substantial.

The surface area multiplied by the above unit cost provides an approximate contract item cost. Assuming a conservative unit cost of $50 per sqft and the average penstock area of 35,000 sqft, Reclamation's average relining cost is $1.75 million per penstock. The estimated total replacement cost for relining all of Reclamation's penstocks is approaching $0.5 billion.

2.1 Reclamation Assets and Relining History

Reclamation maintains 188 penstocks with an average penstock age of 68.2 years old. Figure 2-2 displays the age of Reclamation's penstocks by region, as of 2021. Most penstock interiors received a coal tar enamel lining during construction, which provided the longest possible service life of available linings. Reclamation early research estimated the coal tar enamel to be a permanent lining (Reclamation, 1976). Practically speaking, the expectation was a service life of more than 50 years. Other lining systems, by comparison, were thought to provide 20 years of service and have added maintenance (Reclamation, 1977, p. 46).

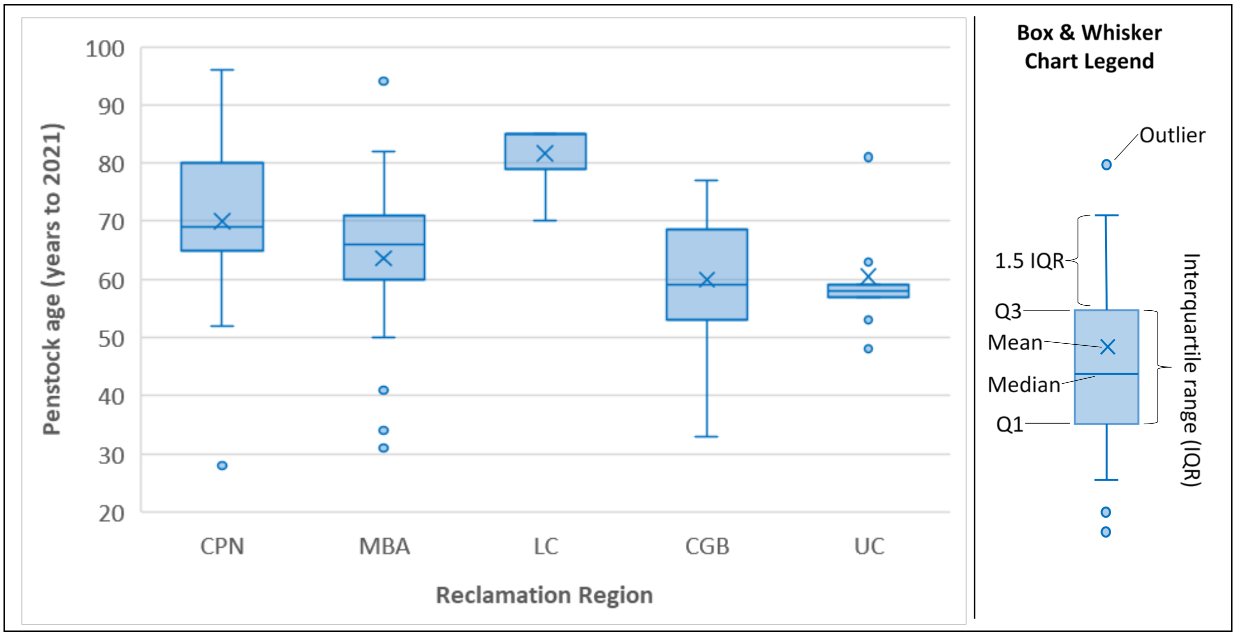


Figure 2-2. Reclamation penstock age (2021 basis) by region

An updated coal tar enamel lining service life based on actual performance may be 50–100 years (Merten B. J., 2017). The service life for new lining materials is likely nearer to 20–50 years—a combined effect of shorter services lives and an aging, corroded condition of the penstock interior surfaces. Budgeting and decision-support tools will help to understand the timing and cost for penstock relining and spot repair contracts across the inventory.

Coal tar enamel remains in service today on an estimated 65 percent of Reclamation's penstocks. In the 2000s, several facilities contracted with painting companies to reline penstocks. The relining jobs used modern linings instead of coal tar enamel—the driving factor for not using coal tar enamel being safety regulations to protect workers from harmful fumes during confined space work (Goldfarb, Konz, & Walker, 1979). The transition began during the 1970s and 1980s across the industry, and coal tar enamel applied today is largely shop applications and exterior coatings for buried pipe (Merten B. J., 2017).

An additional change in penstock relining jobs that began in the 2000s was the utilization of robotic technologies. The long stretches of uniform diameter accommodate automated processes well, and the use of robotics has the added benefit of improving worker safety. There is a growing trend in recent years for contractors to choose robotics, especially for abrasive blasting. The change in lining material and the introduction of robotics have potentially significant cost implications.

Figure 2-3 illustrates a typical penstock or pipe lining lifecycle. The total removal and replacement, i.e., relining, is the start of the lifecycle. With each new lifecycle, spot repairs may occur in the first year of service to address areas with latent defects—this cost is generally covered under the Government's one-year warranty for contracted relining jobs. Afterward, spot repairs could be included in the facility's regular maintenance. Toward the end of a lifecycle, contracted spot repairs could extend the lining service life. After one to two spot repairs per lifecycle, it is not practical or cost-effective, and relining is needed.

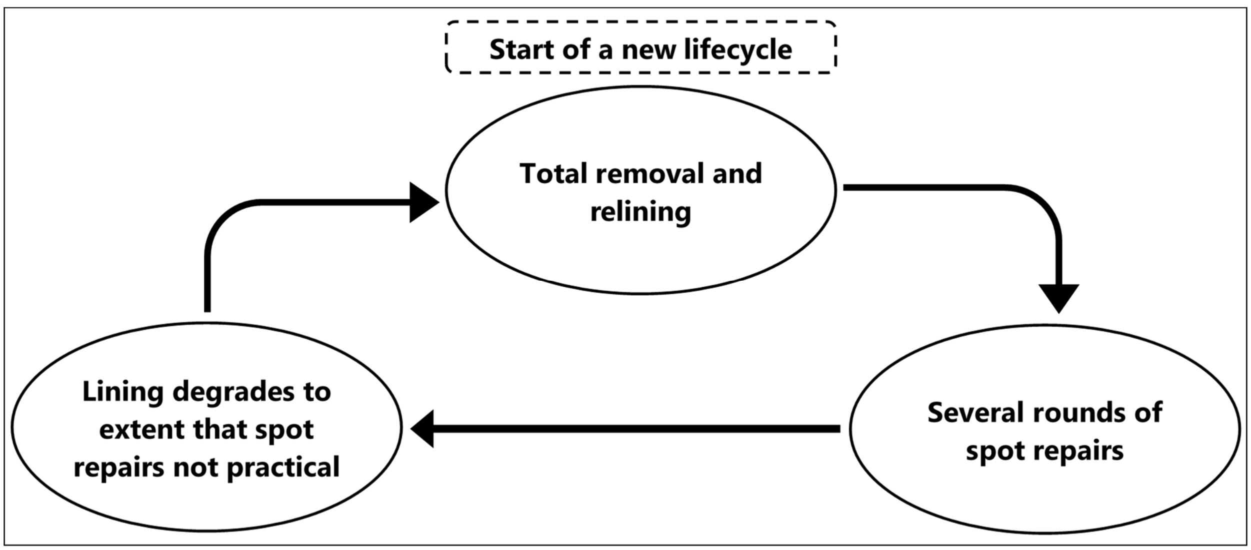


Figure 2-3. Schematic of the penstock or pipe lining maintenance lifecycle

As an alternative to the lining lifecycle depicted in Figure 2-3, the decision could be made to not maintain the lining. This could entail omitting all lining maintenance activities, including spot repairs and the total removal and relining. In this case, the lining continues to degrade, and at some point, corrosion degradation of the steel increases and accelerates via corrosion pitting and undercutting.

Not maintaining the lining is not recommended and the consequence of not relining is progressive deterioration of the steel pipe's structural integrity, and it will eventually require repair. The cost of restoring the steel by weld repairs and section replacements will not be studied in this research and is assumed to be substantially greater than lining maintenance. In extreme cases, restoration is cost-prohibitive, and the structure must be removed from service. Future research could evaluate the benefit-cost of large diameter pipe relining jobs versus a no action "run-to-failure" alternative.

2.2 Prior Reclamation Research and Current Objectives

The present work builds upon the results from S&T Project 4724, Tools and Techniques for Evaluating the Cost of Corrosion Control on Penstocks and Gates, which focused on economic analyses of protective coatings and cathodic protection systems on Reclamation's steel structures (Merten, Gaston, & Torrey, 2018). Project 4724 also performed a preliminary econometric analysis, finding that the cost of recoating water infrastructure depended on a multitude of variables. Further, determining the effects of these variables would require systematic analysis of a larger dataset to develop a robust regression model for forecasting costs.

The initial investigation suggested a negative correlation between square-footage of coated area and per-unit recoating cost, but the small dataset did not allow for differentiation in economies of scale in surface area, penstock diameter, geographic region, etc. However, a regression model based on an adequately large dataset could address previous limitations.

In addition to the preceding relationships, this work also aims to answer the following two primary questions:

1. What are the major cost drivers for the protective coating contracts, and how are they impacted by facility-specific variables, i.e., structure type, access, repair area, percentage of structure being repaired, etc.?
2. What are the estimated future corrosion protection costs at Reclamation?

This research will attempt to answer Question 1 by conducting an econometric analysis of historical corrosion protection costs and related variables for water infrastructure. The results of this analysis will inform the development of a final regression model that can be used to predict future corrosion protection costs—answering Question 2.

An additional, secondary research objective is to determine the economic break-even point for performing spot repairs versus a full reline. Specifically, at what percentage of lining degradation (as a proportion of total interior surface area) is it more cost effective to perform a full reline? If the dataset assembled for evaluation of Questions 1 and 2 contains sufficiently varied observations for spot repair and full relining, then the model can determine this break-even point.

The research team hypothesizes that:

- Relining unit costs have increased over time in real dollars due to multiple factors, including safety regulations, environmental regulations, and escalating construction costs (beyond the rate of inflation).
- Large pipe physical dimensions, namely diameter and slope, are significant drivers of relining costs, with unit costs increasing with steeper grades and larger diameters.
- The use of robotics leads to lower unit costs.
- More complex jobs will have a greater discrepancy between contract award cost and final cost.

2.3 Previous Studies on Cost of Corrosion in Infrastructure

Previous work examining direct cost of corrosion and its associated factors has focused on different engineering applications and sectors including infrastructure, utilities, transportation, production and manufacturing, and government. Each study quantified corrosion cost as expenses resulting from one or multiple factors including equipment and structure replacement, loss of product, maintenance and repair, corrosion control, designated technical support, design, and insurance (Koch, Brongers, Thompson, Virmani, & Payer, 2005). While there is no established or recommended approach to estimating direct cost of corrosion, the few available have assessed cost of corrosion in terms of corrosion costs, control methods, and services or corrosion costs in individual industrial sectors. The four well-known methods that have been used extensively to estimate cost of corrosion are: the Uhlig, the Hoar, National Bureau of Standards – Battelle Columbus Laboratories (NBS-BCL) Input/Output, and the net present value (NPV) method (Bhaskaran, Palaniswamy, Rengaswamy, & Jayachandran, 2005; Biezma & San Cristbal, 2005).

Each method of estimating cost of corrosion uses a different approach depending on the setting. The Uhlig's method calculates corrosion related costs based on corrosion prevention methods and services. This method offers a conservative estimate of corrosion cost. Hou et al. (2017) is an example of a recent study that has used the Uhlig's method to estimate direct cost of corrosion. The study estimated the direct cost of corrosion in China based on data obtained on major anti-corrosion technologies used by the industries involved. The Hoar method on the other hand, requires direct interaction with the industry and can estimate the cost of corrosion for various industrial sectors. The Hoar method depends on data obtained from industry experts. Corrosion cost estimates from the Hoar method are said to be higher than that from the Uhlig method. The NBS-BCL input/output method of estimating corrosion cost is a simplified general equilibrium model of an economy that presents how different sectors interact in terms of demand and supply of inputs and outputs. With the input/output method, the level of uncertainty regarding computation of the capital cost and intermediate output increases. Kim et al. (2011) applied three methods—Uhlig, Hoar, and NBS-BCL—to estimate corrosion cost in terms of percentage of the gross domestic product of the Korean economy.

The fourth method, which is the NPV allows analysts to compare different facilities in terms of cost-effectiveness in corrosion control using life cycle cost analysis. Zayed et al. (2002) employed the NPV method to compare different alternative strategies for steel bridge paint systems using data from the Transportation Departments of the states of Indiana and Michigan. Merten, Gaston, Torrey, & Skaja (2017) also used the NPV method to evaluate cost-effectiveness of corrosion control measures in hydroelectric penstocks of Reclamation.

Given the few available studies on corrosion costs, one of the knowledge gaps is econometric approaches to predicting/forecasting cost of corrosion. To the best of our knowledge, no study has used an econometric approach to predict cost of corrosion in terms of corrosion control measures such as relining. Bhaskaran et al. (2005), for instance, have attempted investigating functional forms to predict cost of corrosion and revealed that a 40-year data study on corrosion costs in the United States exhibited a polynomial growth behavior. This current effort uses an econometric approach to investigate impacts of exogenous factors—including physical features, application technology, and type of lining material—on relining costs for large diameter pipes.

3 Data Collection and Aggregation

Data for this work are organized into two general categories: relining job data and physical feature data. Relining job data are related to a specific large pipe relining job, such as area relined, awarded contract cost, and final contract cost. Physical feature data are inherent to the large pipe feature and include data as specific as length and diameter of pipe subsections and as general as the geographic location of the facility and the operating entity. Data were collected from multiple sources including, but not limited to, relining job award and final contracts, job specifications, facility and infrastructure drawings, and various databases.

For the purposes of this study, the term "relining job" is defined as work that has been contracted-out to rehabilitate or replace the interior protective coating (i.e., lining) of large steel pipe. The costs of relining job contract support activities performed in-house (i.e., non-contract costs) are not included in this analysis, nor are costs for coating maintenance activities not contracted out (performed by an agency's own staff). In general, a single relining job consists of the relining-related work specified in a single contract. A single relining job can result in multiple observations for analysis, as described later in this section.

Multiple partners collaborated in this research project through their provision of relining contracts, summaries of contract data, and complementary drawings. The participation of partner agencies not only provided the research team with a more comprehensive dataset but allowed for the investigation of interagency effects. Representatives of partnering agencies provided data by organization-approved means, which was verified by study leads through discussion and question-and-answer to ensure data conformed to the study approach and method. Table 3-1 summarizes the primary data source types from which this study drew data, the raw data format, whether this source type was provided by Reclamation, study partners, or both, and which study data category it contributed to.

Table 3-1. Data source types by format, contributor, and how it was categorized

Data source type	Format	Maintained by/received from		Data category for analysis	
		Reclamation	Partner agency	Relining job data	Physical feature data
Relining job contract (including schedule of values, specifications, and drawings)	Contract	X	X	X	X
Mechanical Equipment Penstock Database	Database	X			X
Relining job summary (informal)	Email or sum. doc.	X	X	X	
Facility/feature drawings (plan or as-built)	Drawings	X	X		X
Expect Program (TSC Estimating Services Group)	Program output	X		X	
Relining job schedule of values (formal)	Table	X	X	X	
POMTS (Hydropower) Unit Database	Database	X			X

Collected data were input to a master spreadsheet consisting of two primary datasets—a relining job dataset and a physical feature dataset. Relining job data were organized by job contract (contract name and/or contract number when available), while physical feature data were organized by the facility where the feature exists (e.g., Flatiron Powerplant) and then by primary feature description (e.g., Unit 1 Penstock, Unit 2 Draft Tube, etc.). This is an important distinction, as a single relining job might include the relining of more than one feature. Furthermore, a single facility (e.g., powerplant) might have multiple different relining jobs occurring in different years and on different primary features.

Observations for analysis were constructed from the relining job and physical feature datasets, with the primary criteria for constructing an observation being the large pipe feature(s) included in an award cost line item at the highest level of specificity. For example, a relining job contract might include the relining of a penstock and its adjacent outlet tube as a single line item with a single award cost reported, resulting in one observation. Alternatively, a relining job contract might provide two different line items with associated award costs for each of a facility's two penstocks and its adjacent outlet tubes, resulting in two observations.

As stated in Section 2.2, a principal hypothesis of this research project is that more complex relining jobs will have a greater discrepancy between contract award cost and final cost. Therefore, in any case where an awarded relining job had associated final cost data available, a second observation was constructed reflecting the final contract cost and relining details. Table 3-2 provides an example of the construction of six observations from relining job data and physical feature data. Note that relining job data for a given feature can vary depending on whether the observation is developed from award or final, while physical feature data are inherent to the feature and remain constant.

Table 3-2. Example of observation construction from relining job and physical feature data

			Relining job data					***Physical feature data***		
Obs. #	**Facility name**	**Feature description**	**Cont-ract #**	**Award/ final**	**Spot rep./ full reline**	**Area relined (sqft)**	**Relining cost**	**Total area (sqft)**	**Diam. (ft)**	**Slope (deg.)**
1	Okay Powerplant	Unit 1 Penstock	A	Award	Spot	5,000	$300,000	20,000	13	13
2	Okay Powerplant	Unit 1 Penstock	A	Final	Spot	6,500	$357,500	20,000	13	13
3	Jolly Powerplant	Unit 1 Penstock	B	Award	Full	17,000	$680,000	17,000	8	24
4	Jolly Powerplant	Unit 1 Penstock	B	Final	Full	17,000	$730,000	17,000	8	24
5	Jolly Powerplant	Unit 2 Penstock	B	Award	Full	17,400	$700,000	17,400	8	23
6	Jolly Powerplant	Unit 2 Penstock	B	Final	Full	17,400	$770,000	17,400	8	23

In summary, a single relining job can result in multiple award cost observations, and equally as many final cost observations. Available data allowed for the development of 73 award cost observations and 16 final cost observations. The discrepancy is because some relining jobs have only been awarded and the work is not yet complete or final data were not made available to the research team.

The following sections describe the collection and aggregation of relining job and physical feature data into the respective datasets.

3.1 Relining Job Data

This study analyzed 73 large pipe relining jobs from four water management agencies. Contracts for 3.5-ft to 40-ft diameter pipe relining and rehabilitation jobs provided source data for this study. The specific information utilized in these contracts included Section B (i.e., Price Schedule), standard form (SF) 1442, and related technical specification sections (e.g., Division 9). Some of the considerations in the collection of relining job data are discussed below.

3.1.1 Relining Job Complexity

In some cases, large pipe relining work is one part of a greater construction contract, and sometimes a relatively small portion of the total work and cost of a contract. For example, penstock spot repair or relining might constitute less than 25 percent of a contract (in terms of award cost) to perform a complete electrical overhaul of a powerplant's hydropower units. In such instances, the costs specifically attributable to relining work are reported as Section B line items. However, there are comingled costs (e.g., mobilization and demobilization) for such projects that are not clearly attributable to specific work which must be considered carefully. Furthermore, these larger construction jobs can involve multiple subcontractors.

Relining job contracts used in developing the observations for this study generally fall into one of three categories (listed from least to most complex in terms of relining data acquisition):

1. Relining job is sole purpose of contract and awarded to the contractor performing the relining work.
2. Relining job is primary purpose of the contract; prime contractor performs management and peripheral work but subcontracts the relining work—or some other combination of prime and subcontractors.
3. Multifaceted project for which relining work is one aspect of the total work performed; often includes multiple subcontractors.

3.1.2 Project Delivery Method

The 73 relining jobs constituting the study sample were solicited, awarded, and paid-out through multiple different project delivery methods (PDMs). A PDM defines the roles and responsibilities of the parties involved in a project and establishes an execution framework in terms of sequencing of design, procurement, and construction (Oyetunji & Anderson, 2006, p. 1). A review of the literature finds that there are a multitude of PDMs, with the three most frequently mentioned being construction management at risk (CMAR), design/build (DB) and design/bid/build (DBB).

The PDM utilized for a relining job may have some effect on the overall contract cost. For example, a mechanism that requires greater administrative effort by the contractor could result in a higher cost. Oyetunji & Anderson (2006) find that "The decision made in the selection of a project delivery system for a project impacts all phases of execution of the project and greatly impacts the efficiency of project execution." A study sponsored by the National Institute for Standards and Technology (NIST) investigating the impacts of PDM selection on project performance found that owner-submitted DB projects outperformed DBB projects in cost, schedule, changes, rework, and practice use, while contractor-submitted DB projects overall outperformed DBB projects in changes, rework, and practice use (Thomas, Macken, Chung, & Kim, 2002).

The study sample suggests that a given agency can employ more than one PDM but tend to rely primarily on a single preferred method. For example, 83 percent of the Reclamation relining jobs in the study sample utilized a negotiated bid type of PDM, executed as a request for proposals, while the remaining 17 percent were carried out through an IDIQ (indefinite date, indefinite quantity)—a type of open-ended contract PDM. Table 3-3 provides a summary of common PDMs and indicates those represented in the study sample.

Table 3-3. Common project delivery methods and those represented in relining job sample

Project delivery method (PDM) and description	Represented in sample
Quality-Based Selection (QBS) • Low bidder does not necessarily win contract • Generally, for small to medium projects • Price is generally established by the contractor's bid and not negotiated	X
Request For Proposals (RFPs) • Contractor's technical proposal evaluated for experience, schedule, construction methods, etc. • Generally, for medium to large projects or those with safety or other complexity concerns • Low bidder does not necessarily win contract • Contract price may or may not be negotiated	X
Design, Bid, Build (DBB) • Separate contracts for design and construction • Design firm delivers 100% design before project goes to bid for construction • Owner bears risk associated with completeness of design documents • Designers and contractors bear no contractual obligation to one another • Typically, lowest responsive and responsible bidder is awarded construction contract	
Construction Manager at Risk (CMAR) • Negotiated contract based on qualifications • Begins with request for qualifications then firms provide statement of qualifications • Generally, include a guaranteed maximum price (GMP) • One CMAR can have multiple GMPs (e.g., for different steps in the process)	X
Design-Build (DB) • A single entity is hired to perform both design and construction under a single contract • Portions or all the design and construction may be subcontracted to other entities • High levels of collaboration between the design and construction disciplines (typically) • Single entity bearing project risk	
Indefinite Date, Indefinite Quantity (IDIQ) • Acquisition process results in an established contract to which new task-orders can be added at any time • Each task order is negotiated	X
Job Order Contract (JOC) • Uses agency's design • Contractor chosen from pre-approved list (e.g., from other municipalities) • Negotiated similar to the CMAR • Generally, for smaller projects (<$3M)	

3.1.3 Lining Type

The existing lining type can affect the labor and material costs for the contractor removal prior to new lining application. Many Reclamation penstocks contain the coal tar enamel applied at the time of construction. Coal tar enamel is relatively thick by comparison to other linings and can be challenging to remove efficiently. However, there are unique cases in which the original penstock lining was vinyl and low-flow pipelines may instead be lined with a thick and heavy coat of cement mortar lining. The original lining has been replaced at several facilities with alternative linings such as epoxy or polyurethane. The lining material being removed during a relining job may affect project costs due to level of effort (i.e., labor), or disposal costs.

Likewise, the new lining type selected impacts several factors for the contractor. These may include the number of coats applied, total volume of material needed, and the extent of environmental controls needed, e.g., dehumidification or ventilation. The most common new lining material is epoxy. Lining materials less commonly used include vinyl and polyurethane.

3.1.4 Data Acquisition through the Contract Lifecycle

The study captures contract data at two specific times in the contract's lifecycle. The first is at the time of contract award, indicated by the signed date of the award. The second is the final contract, i.e., the work is 100 percent completed and closed out. The final contract includes change orders or contract modifications during project execution, resulting in contract changes between award and final that result in cost increases or decreases.

As reported in Table 3-1, relining job contracts contribute to the collection of both relining job cost data and physical feature data. Figure 3-1 depicts the relining process—from the decision to reline through project close-out—and identifies the points in the process from which relining job data and physical feature data are obtained.

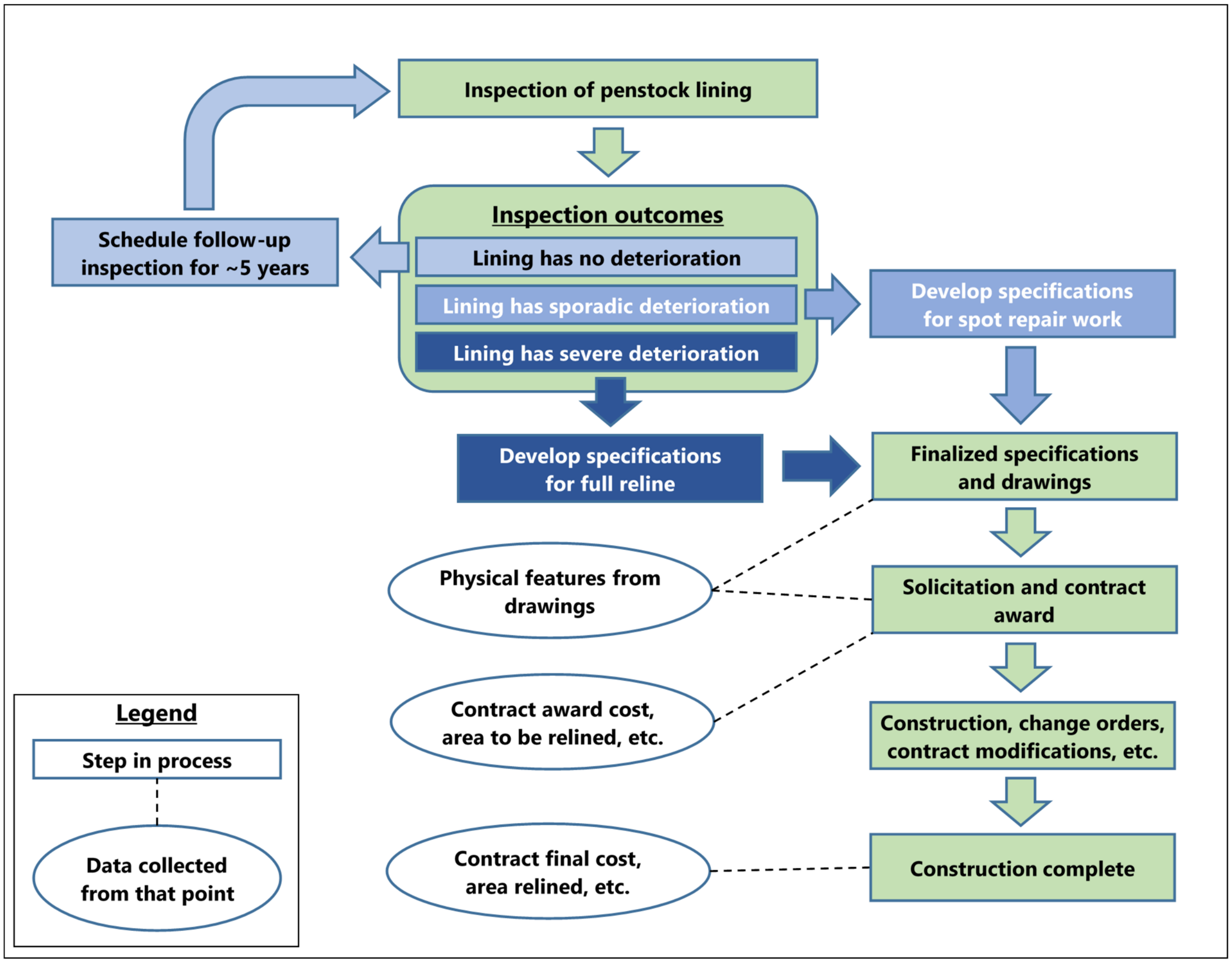


Figure 3-1. Diagram depicting penstock lining maintenance process and data sources for research study

3.1.5 Expect Database

Expect is a program maintained by Reclamation Technical Services Center (TSC) Estimating Services Group. Expect contains bid abstract data primarily from Reclamation solicitations for construction. Expect also contains TSC Estimating Services Group Independent Government Cost Estimates (IGCE) data. Expect provides a statistical evaluation of the unit price for each contract line-item number (CLIN) based on bids from multiple bidders (minimum three bidders to be useful), removes the outliers, and returns a statistically meaningful value ("Expected" unit price). Expect program results are saved in Expect database using Microsoft Access. Expect database displays (for each CLIN) the IGCE unit price, Expected unit price, and CLIN bid prices from three lowest total bids (sum of all CLINs).

Expect data were not used in the econometric analysis for the following reasons:

- Expect data were not compatible with data obtained from research partners outside of Reclamation and other sources.

3.1.6 Summary of Relining Job Data Items Collected

Table 3-4 presents a selection of the contract data items collected (when available) for each relining job. Appendix B reports a comprehensive list of the data items collected along with a definition, input format, and description of importance for each.

Table 3-4. Selection of contract data items collected and descriptions

Data item	Description and context
Contract cost year	The year in which the contract is awarded; provides the basis for indexing all observations to a common price level for equivalent comparison.
Area relined	The sqft of large pipe interior that is relined per award contract specification. If the project has closed out and the actual (final) area relined is available, this is also recorded.
Total contract cost	The sum of all costs included in the contract, including those items not related to relining work.
Relining cost	Summation of relining costs in the contract, including water jetting or cleaning, abrasive blasting, coating application, and ventilation.
Robotics usage in relining	Whether robotics was utilized to remove existing coating, perform surface preparation, or apply new coatings; includes the use of manned or unmanned robotics. Usage of robotics can impact project completion time, efficiency, feature accessibility, and safety.
Mobilization and preparatory cost	Portion of the contract cost that goes toward contractor mobilization and preparatory work. Can vary based on many project conditions including site and structure access, whether there is work other than relining, contract type, type of existing and new coating, etc. This does not include preparation of the surface to be relined, which is included in the *relining cost*.
Existing lining type	The general category of coating system that was removed and replaced during the project, e.g., coal tar enamel, vinyl, cement mortar, etc. Implications include the level of effort to remove and hazardous materials abatement and disposal.
New lining type	The general category of coating system that was newly applied during the project, e.g., coal tar enamel, vinyl, epoxy, etc. There are both preparation and application implications of lining choice, including for surface preparation, environmental control, number of coats, and safety.
Relining job type	Indicates whether the contract is for a spot repair (multiple small areas) or full relining (approximately the total interior area of the large pipe). Spot repairs may be completed in less time than a full relining and require less material, but mobilization and other costs do not scale in proportion to size of area relined. New pipe installs were not included because they do not include removal and disposal of existing coatings and are often lined offsite.
Scaffolding use	Whether or not scaffolding was utilized as part of the lining work. Construction, use, and tear down of scaffolding may represent an increase in project time and costs. Use of scaffolding may also introduce additional safety considerations.
Contracting mechanism	The general category of contracting mechanism employed to solicit, award, and paid-out the contract, including open-ended contracts, negotiated bid contracts, and sealed bid contracts. See Table 3-3 for a summary of common contracting mechanisms.
Water control cost	Indicates the total cost of materials, construction, deconstruction, etc. of any work related to controlling water to enable coatings work to be performed.

3.2 Physical Feature Data

As stated in Section 2.2, a principal hypothesis of this research project is that the physical characteristics of large steel pipes influence the unit cost of relining. Physical feature data were collected and synthesized for the 73 large pipe features for which relining job data were obtained. These data were acquired primarily from drawings and Reclamation databases, and in a few cases were provided as tabulated line items or descriptions from experts familiar with the feature.

3.2.1 Physical Features Not Included due to Insufficient Data

Several physical characteristics inherent to a facility based on geography, climate, and water quality were considered as potentially significant to relining job cost, but insufficient data availability precluded their inclusion in this study. Examples include water salinity, sedimentation rates, water and air temperature, and geographic accessibility (i.e., remoteness of the facility).

Additionally, the concept of feature accessibility—the ease of access for mobilizing relining equipment and personnel to appropriate locations within the large pipe feature—arose frequently with research partners as a potential cost driver. The number of access points (manholes, outlets, ends, etc.) and distance between access points were investigated as potential data items to develop an accessibility variable. However, such a variable could not be developed in a consistent way across the study sample to be used in this analysis. Additional investigation of this topic might prove fruitful for future research efforts.

3.2.2 Summary of Physical Feature Data Items Collected

Physical feature data can be generally organized into three tiers. From broadest to most specific, these are facility-level data, primary feature data, and component feature data. A given facility (e.g., Flatiron Powerplant) comprises multiple primary features (e.g., Unit 1 Penstock, Unit 2 Draft Tube, etc.), and a given primary feature comprises multiple component features (e.g., Unit 1 Penstock Inlet, Unit 1 Penstock 30x25 Reducer, etc.). The physical feature dataset therefore consists of three data subsets: Facility Database, Primary Feature Database, and Component Feature Database. The tables below present a selection of the physical feature data items reported in each of the three databases (when available) for each relining job.

Table 3-5. Selection of physical feature data items reported in the Facility Database

Data item	Description and context
Facility name	The name of the facility housing the large pipe feature analyzed. For water conveyance projects this name describes the dispersed conveyance system.
Facility type	The dataset includes 7 facility types: conventional powerplant, storage reservoir, conventional/pumped-storage powerplant, pumping plant, storage dam, pumped-storage powerplant, and water conveyance.
Ownership	The entity that holds title to the facility.
Contracting entity	The entity responsible for contracting relining work for the facility. This is most often the owner, but that is not always the case. For example, Reclamation holds title on some facilities that are operated and maintained by other entities.
Municipality	The most specifically defined municipality in which the facility falls, or closest proximity.
State/country	The state and country in which the facility is located.
Region	The Reclamation region in which the facility is located. For non-Reclamation facilities, this is the Reclamation region that geographically encompasses the facility.
Project	The Reclamation Project that the facility is a part of (if applicable).
In service date	The year (and month if available) that the facility was completed and began operation.

Table 3-6. Selection of physical feature data items reported in the Primary Feature Database

Data item	Description and context
Feature type	The dataset includes 12 primary feature types: penstock, outlet pipe, draft tube cone, tunnel, scroll case, discharge pipe, draft tube, manifold, vertical elbow, turbine pit, siphon, and conduit.
Feature description	An identifying name describing the primary feature, e.g., Unit 1 Penstock.
Component features	The number of component features comprising the primary feature. This is dependent on the complexity of the feature. The simplest primary features (i.e., straight large pipe with no wyes or changes in slope or diameter) will have no component features.
Direct parent	The primary feature directly upstream of the primary feature of interest (if applicable). For example, Unit 1 Penstock is the direct parent of Unit 1 Draft Tube for a given facility.
Direct dependent(s)	The primary feature directly downstream of the primary feature of interest (if applicable). For example, Unit 1 Draft Tube is the direct dependent of Unit 1 Penstock for a given facility.
Year installed	The year the primary feature was installed. Commonly the same as facility in-service date, but in some cases, features are added after a facility is in operation—sometimes many years after.
Intake elevation and diameter	The feet above sea level and diameter (in feet) at the inlet (upstream end) of the primary feature. These fields are left blank if the primary feature is broken out into component features.
Outlet elevation and diameter	The feet above sea level and diameter (in feet) at the outlet (downstream end) of the primary feature. These fields are left blank if the primary feature is broken out into component features.
Length	The length (in feet) of the primary feature as measured along the centerline from inlet to outlet. This field is left blank if the primary feature is broken out into component features.
Area	The total interior surface area (in sqft) of the primary feature
Slope	The slope (in degrees) of the primary feature, based on length, intake elevation, and discharge elevation along the centerline. This field is left blank if the primary feature is broken out into component features.

Table 3-7. Selection of physical feature data items reported in the Component Feature Database

Data item	Description and context
Component feature type	The dataset includes 9 component feature types: penstock section, vertical elbow section, manifold section, outlet pipe section, outlet tube section, discharge pipe section, draft tube section, siphon section, and pipeline section.
Component feature description	An identifying name describing the component feature and the primary feature of which it is part of, e.g., Unit 1 Penstock Section 1 (Sta. 88+41.50 to 55+67.00).
Component of	The primary feature of which the component feature is a part of, e.g., Unit 1 Penstock.
Component flow order	The numerical position from upstream to downstream of the component relative to all other components constituting the primary feature.
Intake elevation and diameter	The feet above sea level and diameter (in feet) at the inlet (upstream end) of the component feature.
Outlet elevation and diameter	The feet above sea level and diameter (in feet) at the outlet (downstream end) of the component feature.
Length	The length (in feet) of the component feature as measured along the centerline from inlet to outlet.
Area	The total interior surface area (in sqft) of the component feature
Slope	The slope (in degrees) of the component feature, based on length, intake elevation, and discharge elevation along the centerline.

3.2.3 Data Acquisition through Examination of Drawings

The penstock profile drawing presented in Figure 3-2 represents a typical drawing used by the research team to estimate the physical dimension inputs for econometric analysis. The example penstock is somewhat unique in that it has dual-level inlet sections combining at a wye to a common outlet section. This is more complicated than the typical large pipe modeled for this analysis and provides a visually interesting example for presentation.

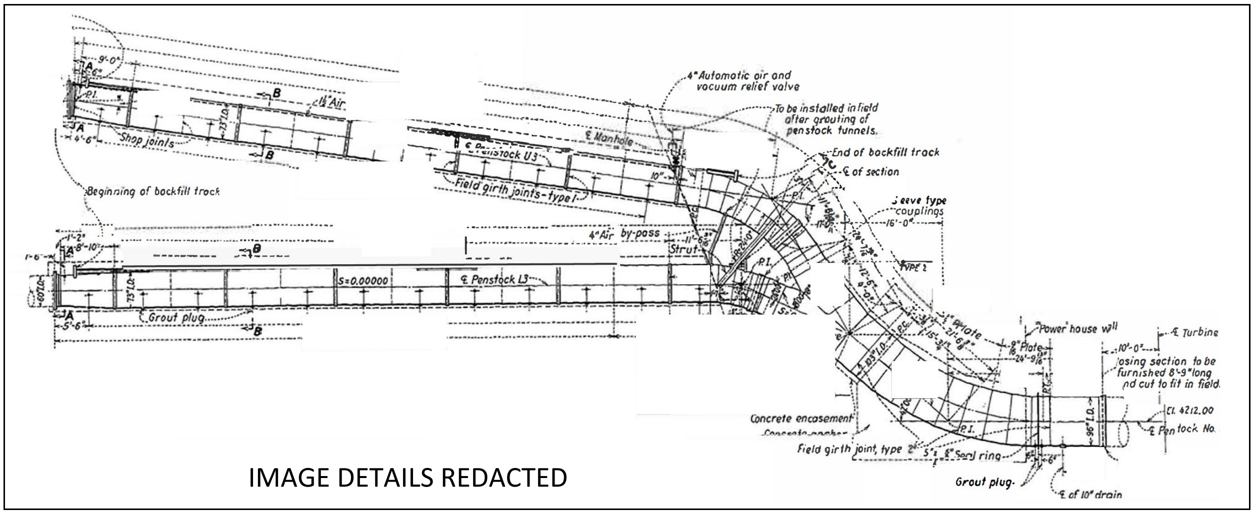
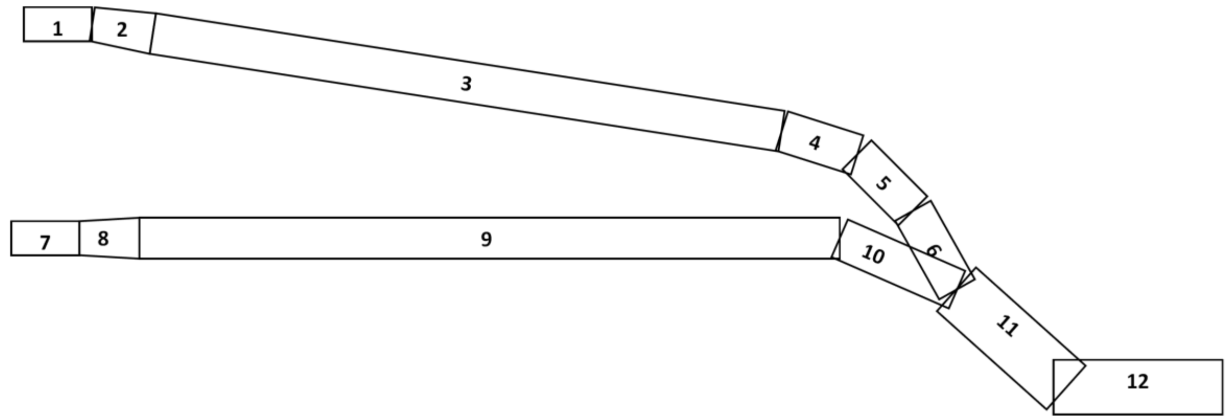


Figure 3-2. Example penstock profile drawing from which feature physical dimensions are estimated

To more accurately estimate the physical dimensions of the large pipes analyzed for this work, each primary feature (large pipe) is broken out into multiple component features. The number of component features is dependent on the complexity of the primary feature. For example, the first component feature is the pipe section beginning at the inlet and ending at the point of first definitive change in diameter, slope, or both. The second component feature begins at the end of the first and continues until the next definitive change in diameter and/or slope.

The simplest primary features in the dataset (i.e., straight large pipe with no wyes or changes in slope or diameter) will have no component features. Figure 3-3 demonstrates the categorization of the drawing presented in Figure 3-2 into component features. The granularity captured by this approach provides the research team with a dataset from which the steepest grades and most extreme diameters are not attenuated by the simplicity of an overall average.



Comp. feat.#	Component feature description	Diameter (ft) Intake	Diameter (ft) Dischg.	Diameter (ft) Avg.	Length (ft)	Area (sqft)	Elevation (MSL) Intake	Elevation (MSL) Dischg.	Slope (% grade)
1	upper penstock inlet sec 1	5.00	5.00	5.00	10.0	157	REDACTED		0.0%
2	upper penstock inlet sec 2	5.00	6.08	5.54	9.0	157			15.0%
3	upper penstock main	6.08	6.08	6.08	93.4	1,784			15.0%
4	upper penstock wye arm sec 1	6.08	6.08	6.08	11.6	222			32.0%
5	upper penstock wye arm sec 2	6.08	6.08	6.08	11.6	222			99.9%
6	upper penstock wye arm sec 3	6.08	6.08	6.08	13.1	250			173.2%
7	lower penstock inlet sec 1	5.00	5.00	5.00	10.0	157			0.0%
8	lower penstock inlet sec 2	5.00	6.08	5.54	8.8	153			0.0%
9	lower penstock main	6.08	6.08	6.08	102.7	1,962			0.0%
10	lower penstock wye arm	6.08	6.08	6.08	18.7	357			44.5%
11	main penstock sec 1	8.58	8.58	8.58	21.5	580			90.0%
12	main penstock sec 2	8.58	8.00	8.29	24.8	646			0.0%
Total						**6,664**			

Figure 3-3. Example of component feature break-out and physical dimension estimation from drawing

4 Methodology

To reline penstocks and other large pipes, water management agencies typically contract with outside entities, generally through a bidding process. The goal of this research is to investigate past contract data for relining penstocks and other large diameter pipes to identify the key cost drivers and develop a regression model that can be used for predicting future relining costs. The average cost paid for past relining work for the study sample is about $84 per sqft, but this varies greatly from $19–$382 per sqft across the sample.

It is worth noting that the research team investigated a relining job with potentially much higher unit costs, on the order of $10,000s per sqft. The anomalously high unit cost was ultimately not included in the sample because the contract included mutually exclusive options for either spot repairs or a full relining—the spot repair option being the anomalously high unit cost. Further, the job proceeded with a full relining, and the agency did not incur the high unit cost for spot repairs.

Regression analysis is used to explore the relining costs sample range and identify key cost drivers. Given the limited work done investigating the variables influencing large steel pipe relining costs (see Section 2.3), stepwise regression analysis is used to test relationships and determine the best functional form for the variables of interest.

Stepwise regression analysis is especially useful when the primary purpose of the model is to estimate the dependent variable (in this case, cost), but can be less reliable for evaluating the effect of specific explanatory variables. Appendix A details the stepwise regression analysis, its limitations, and development of the final model specification—including an overview of the various robustness checks. The present section focuses on the final regression model and predicting future large pipe relining costs.

The regression model developed for this study is considered a reduced form model that estimates the expected cost an agency will face to conduct relining work based on several variables of interest. The cost to the agency is driven by the contractor's cost to complete the work as well as any potential markup. This information is unknown, so a structural model cannot be evaluated. Rather, a hedonic cost function[2] is estimated which captures internal factors of the relining process (e.g., lining type and application method) as well as external considerations (e.g., pipe physical features).

It is important to emphasize that the approach used here is distinct from the approach used by cost estimators to provide formal cost estimates for specific relining jobs. For example, Reclamation cost estimates are prepared in compliance with Reclamation Policy, Directives and Standards, and various guidelines. In general, cost estimators prepare estimates based on input quantities for a particular relining job, accounting for numerous site-specific features, and escalated to a specific budget request year. Conversely, the regression model developed here relies on historical observations and is intended to serve as a "cost calculator" to predict future costs across a wide range of facilities and settings using as few explanatory variables as possible. Some of the variables capture internal features of the process while others account for external factors. The variables selected are those that are generalizable across facilities and most useful for predicting the expected cost for relining. The model predictions are therefore not a substitute for a formal cost estimate.

4.1 Regression Model Overview

The primary focus of the regression model is to identify the relationship between the area relined and the unit cost of relining, measured on a square-foot (sqft) basis. The unit cost is defined as average total cost (ATC), which reflects total cost (TC) divided by the area relined (also referred to as quantity going forward). ATC is unique to each pipe and tends to be much lower for large relining jobs, so the quantity relined is expected to be a key driver of ATC and TC. Additional information is gathered to test the importance of internal and external factors, such as the lining type, pipe physical features, the application process, ownership, location, and the contract year.

Before going forward, it is important to understand that the cost faced by Reclamation may differ from the cost faced by the contractors performing the work. The winning contractor is assumed to

[2] "A hedonic price [cost] function describes the equilibrium relationship between characteristics of a product and its price. They are used to predict prices of new goods, to adjust for quality change in price indexes, and to measure consumer and producer valuations of differentiated products." (Nesheim, 2006)

face standard fixed and variable costs and have control over the inputs used in production (capital, labor, and materials). Meanwhile, the cost Reclamation faces reflects the contractor's costs plus any potential markup (profit margin) for the contractor. Reclamation therefore does not face traditional fixed and variable costs and does not control the inputs used in production. The ATC faced by Reclamation may therefore include a markup and an amount beyond the ATC faced by the contractor, but this is unknown to Reclamation.

If the bidding process is not competitive, then there may be a profit margin (markup) for the winning bidder. However, the bidding setting is generally defined as a monopsony, meaning there is a single buyer and multiple sellers. In this arrangement, it is common for the single buyer (Reclamation) to have bargaining power, in which case the amount paid to the contractor may be competitive and closely reflect their underlying costs. The structure of the bidding process generally follows a first-price sealed-bid action, meaning all contractors provide their bid at the same time and do not know each other's bids. This typically leads to competitive bids that closely reflect the underlying cost for the contractor to provide the work. That said, Reclamation does not actually know the underlying costs faced by a contractor, or if a markup is included in the amount charged. This setting lends itself to a hedonic cost model that focuses on the expected amount Reclamation pays for relining work based on internal and external factors.

A hedonic cost function describes how internal and external factors affect cost and is applicable to competitive and non-competitive settings. The functional form is driven by buyer (Reclamation) preferences, seller (contractor) costs, and the structure of competition (bidding process), which governs the potential for a markup. A hedonic cost function breaks down the item being evaluated across the underlying characteristics and estimates the contribution of each characteristic. The model assumes that the cost reflects embodied characteristics valued by some implicit or shadow prices. In a hedonic regression model, the coefficient estimates reflect the shadow prices on the implicit characteristics. In addition to the quantity relined (*Q*), cost is expected to be a function of pipe physical features (*Phys Feats*), the existing lining and new lining type (*Lining*), and the application technology used (*App Tech*). Cost may also be a function of location, time, and ownership. To test for the importance of these considerations, a hedonic cost function h(.) is specified as:

$$Cost = h(Q, Phys\ Feats, Lining, App\ Tech, Location, Time, Ownership) \qquad (1)$$

This equation states that cost is a function of the quantity relined as well as pipe physical features (diameter, slope, and length), lining type (existing and new), the application technology (robotic versus manual), location (Reclamation region), time (contract year), and ownership (Reclamation or not). There are other variables that would likely influence cost, but the inclusion of additional variables is limited by the data available. Hedonic models can accommodate non-linearity, variable interaction, or other complex situations. When you differentiate the cost function with respect to any one of the characteristics, this yields the implicit price function for that particular characteristic. It is considered implicit because the price function for each characteristic is revealed through the regression model and such a price typically does not actually exist for each characteristic.

Equation 1 can be estimated focusing on total cost (TC) or average total cost (ATC). Since ATC is expected to vary based on the area relined, ATC is the focus of the regression analysis. TC is then calculated as a function of the quantity relined and ATC, which is affected by quantity and potentially other factors (Z) such as characteristics of the pipe, features of the relining process, ownership, location, and time, as shown in Equation 1. The TC to Reclamation for relining pipe (i) is calculated according to the predicted ATC ($\widehat{ATC}$), estimated as a function of the quantity relined and other factors (Z), multiplied by the quantity relined:

$$TC_i = \widehat{ATC}_i(Q_i, Z_i) * Q_i \tag{2}$$

Equation 2 highlights that ATC and quantity are both unique to a particular pipe, and that ATC is a function of quantity and other factors, as estimated by Equation 1. Since quantity influences ATC, the cost function is expected to be non-linear in quantity. If ATC falls as quantity increases, then the cost function exhibits economies of scale, meaning doubling quantity will less than double cost. Economies of scale have been frequently observed for past relining work, which was one of the early motivations for this research.

By using a cross-sectional sample of past pipe relining jobs across a wide range of pipes, the regression analysis serves to estimate Equation 1 and calculate Equation 2. The specification for each hedonic cost model tested is shown in subsequent sections, and after identifying the preferred model, the final regression equation is reported and discussed in detail, and several robustness checks are performed. Before getting into the regression analysis, it is important to first define the variables of interest and establish the theoretical basis for testing each, as well as the a priori expectations for their effect on cost. It is also worthwhile to examine the descriptive statistics for the sample data and visualize the variables of interest.

4.2 Regression Model Data

To examine Equations 1 and 2, the cost for relining a penstock was obtained from past award contracts. This largely comes from past Reclamation relining jobs, but also includes observations from the Central Arizona Project, Metropolitan Water District, and Denver Water. Like Reclamation, these entities manage large diameter pipes and rely on contracting for relining. The information in these contracts is often proprietary, so facility names and contracting entities are not revealed, and the sample data are only described and analyzed at a high level.

The total amount paid for a relining job includes costs for mobilizing and demobilizing resources, water control, hazmat, scaffolding, removal of the existing lining, surface preparation, and application of the new lining.[3] Many of these costs are lumped together in a significant portion of the reviewed contracts, and only a few contractors provide separate cost estimates for each of these line items. For the regression model, attention is therefore placed on the total cost across all items associated with relining. The award date of a contract is used to adjust all values to a 2020$ using Reclamation's CCT, specifically the index for steel pipelines (Reclamation, 2021a). All dollar values reported throughout are therefore 2020$ unless otherwise noted.

The sample used for the regression analysis was constructed using all available contracts that could be identified. This entailed extensive efforts from Reclamation and others partnering on the study to

[3] Mobilization and demobilization cost is often provided as a separate line item. Some contracts include work unrelated to relining, so this amount is proportioned by spending on relining-related work relative to the overall contract amount in order to approximate the portion associated with relining.

gather, organize, and validate the information provided in each contract. Data collection and aggregation is described in detail in Section 3 of the report, while here the focus is on the sample and variables used for the regression analysis. The candidate variables tested in the analysis were limited by the information reported in the contracts. In general, the variables selected were those that were consistent across contracts and potentially useful for predicting future relining costs. The candidate variables are discussed in the next section followed by descriptive statistics for the sample.

A total of 73 observations were identified, each reflecting the cost to reline a particular large diameter pipe, meaning the sample is considered cross-sectional. These observations span 20 contracts and 15 facilities for the period 1999 through 2020. Some of these contracts are complete, while others have only been awarded and the work is not yet complete or final data were not made available to the research team. Treating each pipe relined as an observation is important since each pipe is unique and the cost for relining is expected to depend in part on the features of the pipe. That said, since many facilities in the sample have had numerous pipes relined, the sample structure means that it is potentially important for the regression model to control for differences across contracts and facilities not explicitly picked up by variables included in the model. This also means that various robustness checks are important, such as testing clustered standard errors in the final regression model.

4.2.1 Regression Model Variables

This section provides a brief overview of the candidate variables examined in the regression analysis. As covered elsewhere in the report, additional data and variables were considered, but here the attention is on those variables with the strongest theoretical basis for being predictors of cost. Table 4-1 provides a description for each variable of interest.

Table 4-1. Variable descriptions

Variable	Description
Total Cost (TC)	Total cost of relining measured in dollars (2020$). This includes costs for mobilizing and demobilizing resources, water control, hazmat, scaffolding, removal of the existing lining, surface preparation, and application of the new lining.
Average Total Cost (ATC)	Average cost per sqft of area relined (2020$). This is calculated by dividing TC by the area relined.
Area Relined (Q)	Area relined measured in sqft.
Existing Lining Type	Existing lining type category; coal tar enamel, cement mortar, epoxy, vinyl, or polyurethane.
New Lining Type	New lining type category; epoxy, vinyl, or polyurethane.
Pipe Diameter	Diameter of the pipe measured in ft. Tested transformations of diameter include unweighted (UW), length-weighted (LW), and area-weighted (AW).
Pipe Slope	Slope of the pipe measured in degrees. Tested transformations of slope include unweighted (UW), length-weighted (LW), and area-weighted (AW).
Pipe Length	Total length of the pipe measured in ft.
Robotic	Variable indicating if relining was done using robotic application rather than manual application. This includes using robotic application for removing the existing lining.
Time	Year of the award contract.
Location	Reclamation region that the relining occurs in. State is also examined.
Reclamation	Variable indicating if the pipe is owned by Reclamation or another entity.

The dependent variable of interest is TC, which includes costs for mobilizing and demobilizing resources, water control, hazmat, scaffolding, removal of the existing lining, surface preparation, and application of the new lining. Also of interest is ATC, which is the average unit cost per sqft of area relined. This is of most interest for the regression analysis given the wide range in ATC that has been found for past relining work. ATC is therefore modeled as the key dependent variable of interest. TC is also examined, but as shown later, the final model is identical regardless of using TC or ATC as the dependent variable for the model.

The first independent variable of interest is the area relined (Q). The quantity relined is expected to have a positive relationship with TC and a negative relationship with ATC. A negative relationship with ATC would indicate economies of scale, meaning the cost per unit of output falls as the area relined increases. Put simply, doubling Q less than doubles TC. Relining requires specialized equipment, and every job requires mobilizing resources (capital, labor, and materials), water control, hazmat, removal of the existing lining, surface preparation, and application of the new lining. While some of these costs vary with quantity, many of these costs are incurred regardless of the area relined, meaning they are a large part of the overall job when only a small area is being relined, but a much smaller portion of the job if a large area is relined. The spreading of the high upfront costs is expected to result in ATC falling as quantity rises, i.e., demonstrating economies of scale.

The next variables are for the existing lining type and new lining type. Since relining includes removing the existing lining and preparing the surface, the existing lining type may influence the cost of relining. Meanwhile, the new lining type used might also have important implications due to differences in the cost of materials. Given that there are numerous lining types, each type is grouped under a broad category as being either coal tar enamel, epoxy, polyurethane, vinyl, or cement mortar. There is however a range of lining types within most of these categories, which is more than the modeling can accommodate. Surface preparation is often similar regardless of the existing lining, and the cost of the new lining material is generally a small portion of the overall cost of relining, so there are no a priori expectations for which lining types might result in higher or lower relining cost. Lining type is discussed in further detail in Section 3.1.3.

The next variables are for pipe diameter and pipe slope. Since diameter and slope can vary along a single pipe, a weighted average is considered. An unweighted (UW) measure of diameter and slope was examined, as well as a length-weighted (LW) and area-weighted (AW) measure. For example, if a pipe is 10 ft in diameter and on a 10-degree slope for 50 percent of the length, and then six ft in diameter and flat for the remaining 50 percent, the LW measure of diameter would be eight ft and the LW measure of slope would be a five-degree slope. Since there are only two unique pipe sections in this example that are both the same length, the UW measures would be the same, which gives equal weight to the features of each pipe section, regardless if it is 99 percent of the pipe length or only one percent.

Meanwhile, AW measures reflect the proportion of the area relined done on various pipe sections, which is a function of pipe diameter. In the previous example, based on the length of each pipe the area for each section can be calculated, and AW measures would then give greater weight to the large diameter section. This means the AW measure of diameter would be greater than eight ft and the AW measure of slope would be greater than five degrees, which were the values for the LW and UW measures. None of these methods are perfect, but the LW and AW measures are more appropriate than the UW measures since they consider the proportion of the overall pipe that is defined by a particular diameter and slope, but in different ways. Each of these is examined.

The a priori expectation is that increasing diameter and slope might increase ATC, all else equal. As diameter increases, it becomes more difficult to reach the entire pipe circumference, which may require specialized equipment such as scaffolding and increase the time it takes to move along the pipe. Meanwhile, relining on a steep slope also generally requires scaffolding as well as safety equipment, and is also likely to increase the time it takes to move along the pipe. ATC is therefore expected to be higher the larger the pipe diameter and the steeper the pipe slope. The combination of these two increasing together is also examined to see if there might exist a compounding effect. Pipe length is also examined, with the expectation that a greater length might increase cost due to reduced access, which makes it harder to bring workers and equipment to the area needing relined. That said, pipe length is highly correlated with the area relined, so as discussed later, this variable receives minimal attention and is not included in the final model.

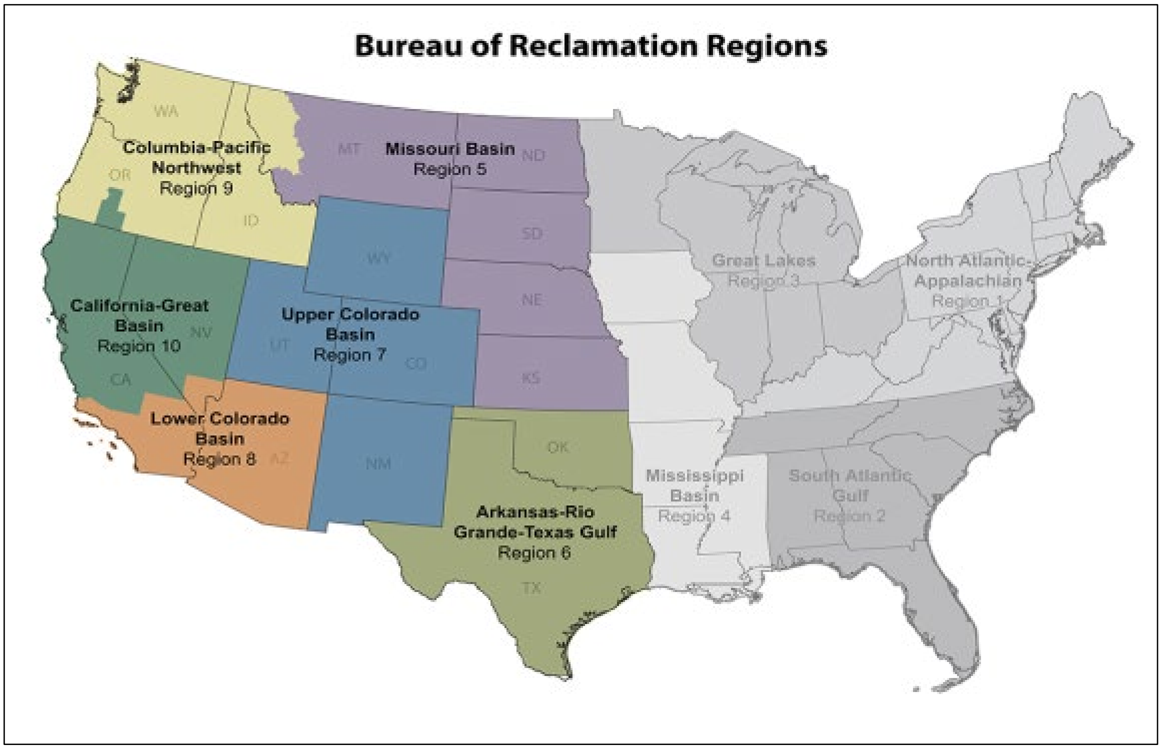
The next variable, Robotic, captures whether relining was done using robotic application or manual application, which also includes whether robotics was used for removing the existing lining. Using robotics to remove the existing pipe lining and apply a new lining is a relatively recent technology. The technology is common for relining small diameter pipes, particularly those that a person cannot fit inside, but only recently have robotics been used for relining large diameter pipes. The motivation for using robotics for large pipes is in part motivated by safety precautions, gaining significant attention in 2007 after five workers lost their lives after getting trapped inside a penstock when a fire broke out at a plant in Georgetown, CO. That said, robotic application is still generally required to be manned, often with workers controlling a winch system that guides the robot. There have been very few instances of using entirely autonomous robotics, and all robotics observations in the sample, which represents about half of the observations, used manned robotics.

While using robotics can help improve safety, there are also some potential cost savings due to factors such as quicker application, less spending on labor, and less waste. However, it could also end up being more expensive since the technology is still being developed and is costly to perfect. Using robotics requires more specialized labor and entails frequent recalibration, especially as pipes change in diameter, which requires recalibrating the sprayers to produce a consistent coating thickness. This means that pipe diameter, and even slope, might affect ATC differently with robotics application versus manual application, which is explored in the regression analysis. The a priori expectation that ATC may differ for robotic versus manual application, but it is unclear which may be the cheaper option, and it may ultimately depend on other factors, such as pipe physical features.

It is important to keep in mind that the use of robotics has not been fully developed at the time of this research, which means that any potential cost savings may not be fully realized. This means that relying on past observations may not provide an accurate picture of the cost of robotics in the future. When it comes to using robotics, there may also be additional benefits over manual application, such as a higher quality and more consistent lining application that results in a longer lifespan. Unfortunately, such effects cannot be tested with our sample and modeling framework that focuses only on the cost of the relining process itself.

Time is also tested as a variable, which reflects the year a contract was awarded. Including this in the model accounts for exogenous macroeconomic trends not explicitly captured by other variables in the model that might influence cost across time for all relining work. This includes the cost for key inputs such as labor, capital, and materials.

The next variable, Location, captures the Reclamation region where the relining job was done. There are five Reclamation regions: Upper Colorado Basin Region (UC), Lower Colorado Basin Region (LC), Columbia-Pacific Northwest Region (CPN), California-Great Basin Region (CGB), and Missouri Basin and Arkansas-Rio Grande-Texas Gulf Region (MBA). The Missouri Basin and the Arkansas-Rio Grande-Texas Gulf are grouped as a single region (MBA) since these areas are commonly grouped by Reclamation and were historically defined as the Great Plains Region. Reclamation regions are displayed in Figure 4-1. State is also examined instead of Reclamation region to account for locational differences. There are no a priori expectations for which regions or states might be more expensive, but the influence of location on cost is explored in case there are any locational differences found for historic observations.



Source: (Reclamation, 2021b)

Figure 4-1. Map depicting Reclamation regions and DOI Unified Region number designation

The last variable, Reclamation, reflects whether a pipe is owned by Reclamation or a non-Reclamation entity. Several factors could result in cost differences by pipe owner. For example, Reclamation is the only entity with spot repair relining jobs represented in the sample data. As explained in Section 2, spot repairs may be an order of magnitude higher unit cost than a full relining for a comparable pipe due to mobilization inefficiencies and fixed costs being spread across a smaller volume of work. Additionally, Reclamation is the only Federal agency represented in the sample data. Federal agencies are subject to the Davis-Bacon Act and the Contract Work Hours and Safety Standards Act, as amended, which dictate terms for wages rates and overtime compensation for federally funded contracts.[4] These two factors, among others, might lead to cost differences between Reclamation and other entities. Ownership is therefore considered a variable of interest for the regression analysis.

The next section examines some descriptive statistics and graphs for these variables to help further inform a priori expectations and highlight any obvious relationships found in the sample data.

[4] Per the U.S. Department of Labor, Wage and Hour Division: "The Davis-Bacon and Related Acts, apply to contractors and subcontractors performing on federally funded or assisted contracts in excess of $2,000 for the construction, alteration, or repair (including painting and decorating) of public buildings or public works. Davis-Bacon Act and Related Act contractors and subcontractors must pay their laborers and mechanics employed under the contract no less than the locally prevailing wages and fringe benefits for corresponding work on similar projects in the area...For prime contracts in excess of $100,000, contractors and subcontractors must also, under the provisions of the Contract Work Hours and Safety Standards Act, as amended, pay laborers and mechanics, including guards and watchmen, at least one and one-half times their regular rate of pay for all hours worked over 40 in a workweek. The overtime provisions of the Fair Labor Standards Act may also apply to DBA-covered contracts." (U.S. Dept. of Labor, 2021)

4.2.2 Descriptive Statistics and Sample Characteristics

As emphasized, the ATC for past relining work varies substantially, ranging from as low as about $20 per sqft for very large jobs, to almost $400 per sqft for very small jobs. In general, the quantity relined is expected to be a key predictor of ATC, along with some of the internal and external factors captured by other variables. Table 4-2 provides some descriptive statistics for the sample data and variables of interest described in the previous section.

Table 4-2. Descriptive statistics

Variable	Average	Min	Max	Standard Dev.
TC ($1,000's)	1,244.53	43.58	8,765.05	1,287.62
ATC ($ per sqft)	85.29	18.58	382.32	61.22
Quantity (sqft)	26,019.33	114	471,804	58,475.96
Existing Lining Type*				
Coal Tar Enamel	0.88	0	1	0.33
Cement Mortar	0.04	0	1	0.20
Polyurethane	0.03	0	1	0.16
Vinyl	0.04	0	1	0.20
Epoxy	0.04	0	1	0.20
New Lining Type*				
Polyurethane	0.08	0	1	0.28
Vinyl	0.03	0	1	0.16
Epoxy	0.90	0	1	0.30
Pipe Diameter (ft)				
Unweighted (UW)	14.07	4	38.40	6.90
Length-Weighted (LW)	14.49	4	39.28	7.16
Area-Weighted (AW)	14.78	4	39.33	7.35
Pipe Slope (degrees)				
Unweighted (UW)	13.34	0	47.98	8.64
Length-Weighted (LW)	18.31	0	41.87	12.33
Area-Weighted (AW)	17.94	0	41.87	12.38
Pipe Length (ft)	1,207.40	85	12,515	1,982.71
Robotic	0.51	0	1	0.50
Time (year)	2017	1999	2020	4.91
Reclamation Region				
Upper Colorado Basin	0.04	0	1	0.20
Lower Colorado Basin	0.19	0	1	0.40
Columbia-Pacific Northwest	0.62	0	1	0.49
California Great Basin	0.03	0	1	0.16
Missouri Basin/Arkansas-Rio Grande-Texas Gulf	0.12	0	1	0.33
Reclamation	0.88	0	1	0.33

*Lining types do not sum to 1.0 since some observations have more than one lining type.

Looking at the descriptive statistics for the sample, on average it costs about $1.24 million to reline a large diameter pipe, but this ranges from about $44,000 to $8.77 million. Note that this includes a handful of observations that are for spot repairs and relining jobs less than the entire pipe area. Although not shown in the table, about 81 percent of the sample observations are for a full reline, while the remainder reflects spot repairs and partial relines. Across the sample, the average ATC is about $85 per sqft, but ranges from $18.58 to $382.32 per sqft. For the quantity relined, the average is just over 26,000 sqft, but the sample ranges greatly from 114 sqft to 471,804.

Looking at lining types, most of the sample observations (88 percent) have coal tar enamel as the existing lining type, and most (90 percent) use epoxy for the new lining type. Note that the lining types do not sum to 100 percent since some observations have more than one existing lining type and one observation includes two new lining types. Given that there is minimal sample variation for lining types, the a priori expectation is that the model may not be able to distinguish effects on ATC between lining types. Nonetheless, there may be some lining types that stand out as affecting cost, so this is explored in the regression analysis.

For pipe physical features, UW diameter is on average 14 ft, while LW diameter is slightly higher at 14.5 ft and AW diameter is almost 15 ft. Diameter ranges from four ft to nearly 40 ft across the sample. Note that 3.5 ft (42-inch) was the chosen cutoff so that the sample and model focus solely on large diameter pipes. Also note that pipe diameter reaches 40 ft for some pipe sections, but since the diameter generally varies across a single pipe, the max diameter for the UW, LW, and AW measures is below 40 ft. For pipe slope, the UW average is about 13 degrees, while the LW and AW average is about 18 degrees. The sample minimum is the same for all of these, at zero degrees, while the maximum is 48 degrees for the UW measure of slope and about 42 degrees for the LW and AW measures. These descriptive statistics indicate that there is a bit more variation across the UW, LW, and AW measures for pipe slope than for pipe diameter. Nonetheless, as covered later, each of these produce similar estimates when included in the regression model. The average pipe length is about 1,200 ft, but ranges from 85 ft to 12,515 ft.

For robotic versus manual application, about half of the sample reflects each application technology. For the contract year, the sample average is 2017, but ranges from 1999 through 2020. There are numerous observations towards the end of the sample period which pulls the average up. Looking at Reclamation region, most (62 percent) of the observations are in the CPN, with about 19 percent in the LC, 12 percent in the MBA, and then only a handful of observations in the UC and CGB. Like the different lining types, Reclamation regions are not well represented in the sample. This is important to keep in mind for the regression analysis and could affect the reliability of the coefficient estimates for these variables.

Lastly, about 88 percent of the sample observations are for Reclamation, with the remainder for other entities in the sample (the Central Arizona Project, Metropolitan Water District, and Denver Water). While Table 4-2 highlights the sample average and range for the variables of interest, it is also important to examine how the data are distributed, particularly for the dependent variable and the continuous independent variables of interest. It is also worthwhile to examine scatterplots of the data to see if any obvious relationships exist.

Since regression analysis focuses on changes around the mean of each variable, it is generally ideal to have minimal skew and sample data that are close to a normal distribution. If skewness is between -0.5 and 0.5 the data are considered symmetrical, between -1.0 and 1.0 are moderately skewed, and if the skewness is outside -1.0 to 1.0 the data are considered highly skewed. A common way to deal with data that are highly skewed is to use a natural logarithmic transformation, which then focuses on the geometric mean of the distribution rather than the arithmetic mean.[5] In general, this helps to reduce potential bias from outliers and allows them to remain in the sample.

A log transformation turns a multiplicative regression model into an additive one, and the coefficient estimate is interpreted as looking at percent changes around the mean. In a log-log regression specification, meaning both the dependent variable and independent variable of interest are specified with a natural log transformation, the coefficient estimate indicates the percent change in the dependent variable associated with a one-percent change in the independent variable. This is typically referred to as an elasticity, which is a measure commonly evaluated in economics using natural log transformations for the variables of interest. Such transformations are also useful for improving the regression model residuals (difference between actual values and predicted values) and reducing heteroscedasticity, which is a non-constant variance in the model residuals that can bias the estimates.

Starting with total relining cost, the sample distribution is positively skewed with a mean of $1.24 million, median of $1.13 million, and a skewness of 3.34. After taking the natural log of total cost, the distribution becomes slightly negatively skewed with a skewness of -0.52, meaning the distribution becomes closer to normal. This means that a natural log transformation is likely warranted if modeling total cost as the dependent variable. Figure 4-2 shows the distribution of total cost in level form (original units) and after a natural log transformation, highlighting that the distribution is closer to normal on a natural log scale.

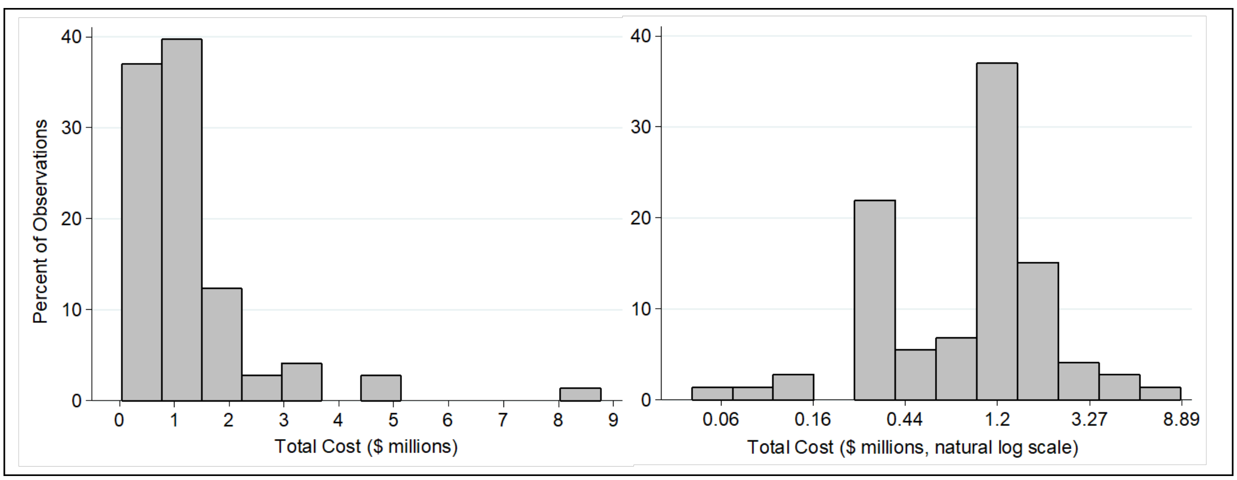


Figure 4-2. Distribution of total cost

While TC is examined as the dependent variable, most of the regression analysis focuses on ATC as the dependent variable of interest. Similar to TC, the distribution of ATC is positively skewed, with a mean of $85.29 per sqft, median of $71.94 per sqft, and a skewness of 3.37. After a natural log transformation, skewness becomes 0.75, bringing the distribution closer to normal. This suggests

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[5] Geometric mean indicates the central tendency or typical value of a set of numbers by using the product of their values, as opposed to the arithmetic mean which uses their sum. The geometric mean is defined as the n^{th} root of the product of n numbers.

that a natural log transformation is again warranted, in this case when ATC is modeled as the dependent variable. Figure 4-3 shows the distribution of ATC in level form and after a natural log transformation, highlighting that the distribution is closer to normal on a natural log scale.

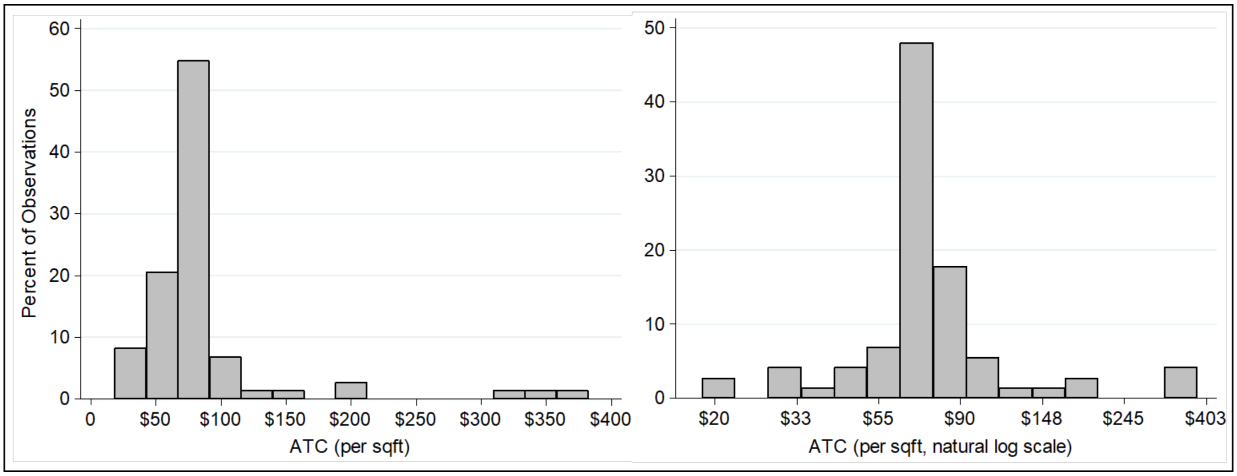


Figure 4-3. Distribution of average total cost (ATC)

Looking at the first independent variable of interest, the quantity relined, the distribution is again positively skewed. The distribution for quantity has a mean of 26,000 sqft, median of 16,400 sqft, and skewness of 6.35. The large skewness is driven by a single outlier with over 450,000 sqft relined. To avoid bias from outliers, a natural log transformation is again examined, which results in a distribution with a skew of only -0.60. A natural log transformation therefore also appears necessary for the quantity relined and doing so allows for potential outliers to remain in the sample. Figure 4-4 shows the distribution of area relined (quantity) before and after a natural log transformation, highlighting that the distribution is much closer to normal on a natural log scale.

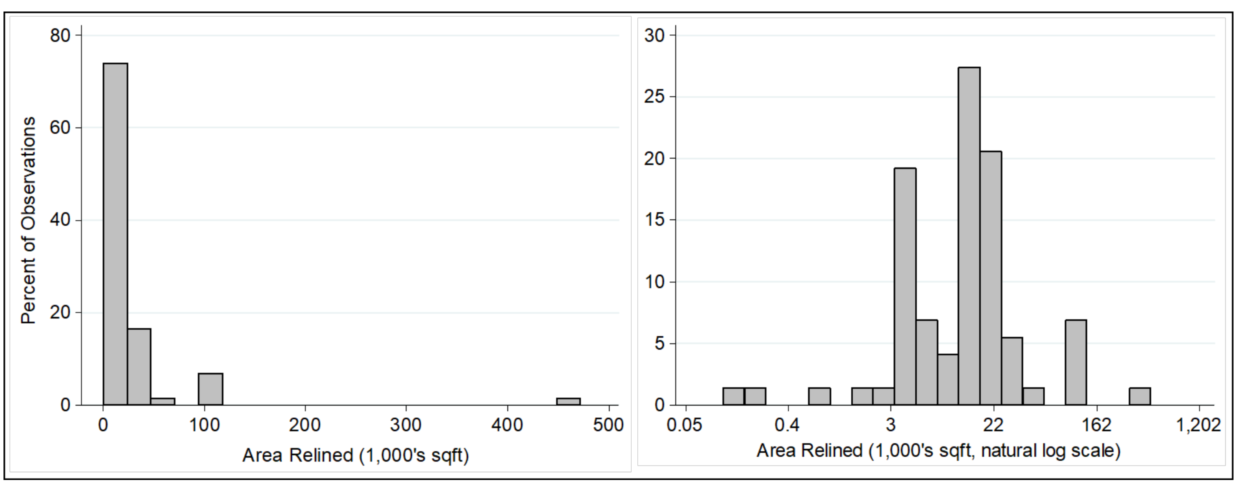
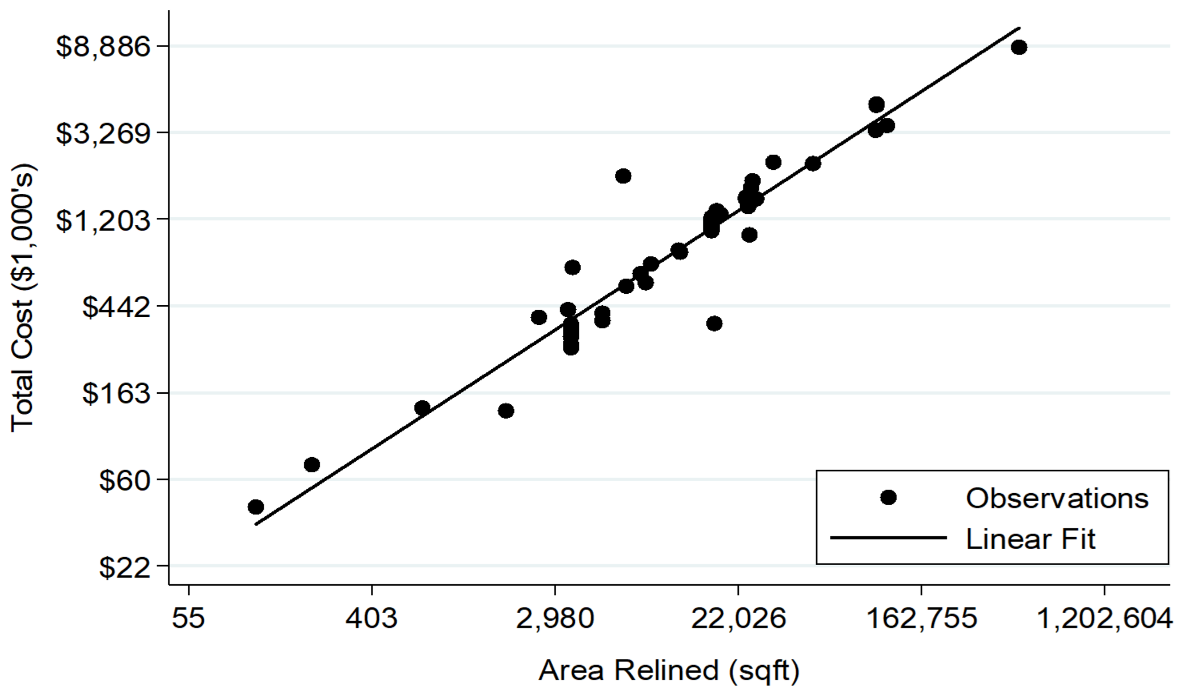


Figure 4-4. Distribution of area relined (quantity)

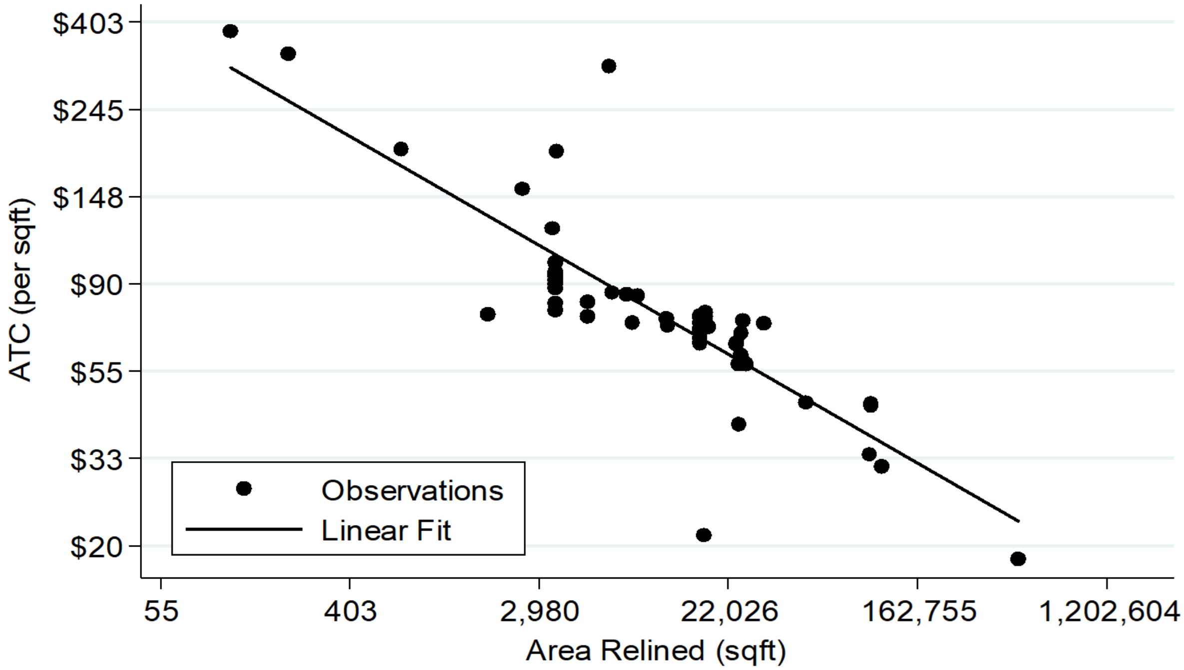
Before looking at other variables of interest, it is worthwhile to examine the relationship between quantity relined and cost. Figure 4-5 shows the relationship between quantity and total cost, both on a natural log scale and with a linear fitted line to highlight the positive relationship.



Notes: Total cost and area relined are shown on a natural log scale.

Figure 4-5. Scatterplot for area relined and total cost

Figure 4-5 suggests that a log-log regression specification between quantity and TC is likely to provide a strong model fit, exhibited by the strong log-linear relationship. There is also a strong log-linear relationship between quantity and ATC, meaning a log-log regression model between these variables is also likely to provide a strong model fit. A negative relationship with ATC would indicate economies of scale, meaning ATC decreases as quantity increases. Since both variables are highly skewed, a log-log regression is again examined. Figure 4-6 shows the relationship between quantity and ATC, both on a natural log scale. As shown, there is a strong log-linear negative relationship.



Notes: ATC and area relined are shown on a natural log scale.

Figure 4-6. Scatterplot for area relined and ATC

These figures are consistent with a priori expectations for economies of scale and indicate that quantity is a strong predictor of cost, exhibiting a strong log-linear relationship. Another important a priori expectation is that increasing pipe diameter and pipe slope might increase cost. The distribution for these variables is examined next.

As previously mentioned, the UW, LW, and AW measures of diameter and slope produce similar model estimates, but the LW and AW measures are more appropriate than the UW measures since they consider the proportion of the overall pipe that is defined by a particular diameter and slope. Although each of these is explored, the AW measures are ultimately deemed the most appropriate since the area relined is a key variable in the model and this proportions the slope and diameter of each pipe section by the area relined in that particular section. Meanwhile, the LW measures treat a small diameter pipe section the same as a large diameter section of equivalent length, even though more area is relined in the large diameter section. Attention is therefore placed on AW diameter and AW slope.

Looking at the distribution of AW diameter, the mean is 14.78 ft, the median is 13.33 ft, and skewness is 1.50. Taking a natural log transformation reduces the skewness to -0.17, but as covered later on, the fit of the regression model is not improved by a natural log transformation, and such a transformation makes the coefficient estimate less straightforward to interpret (measuring percent changes in diameter rather than one-foot increments). Figure 4-7 shows the distribution of AW diameter before and after a log transformation, showing that the distribution is slightly closer to normal on a natural log scale.

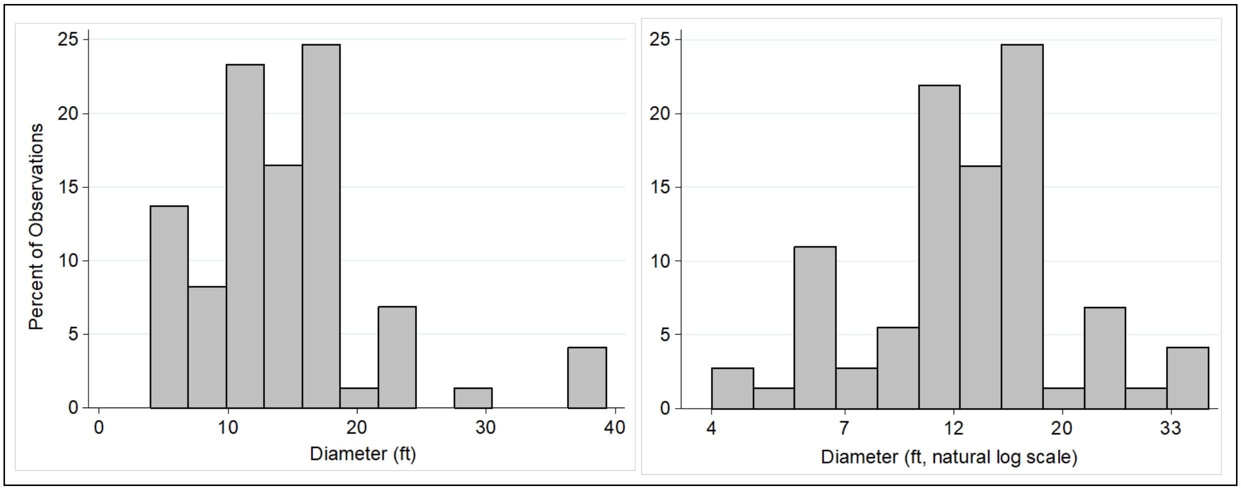
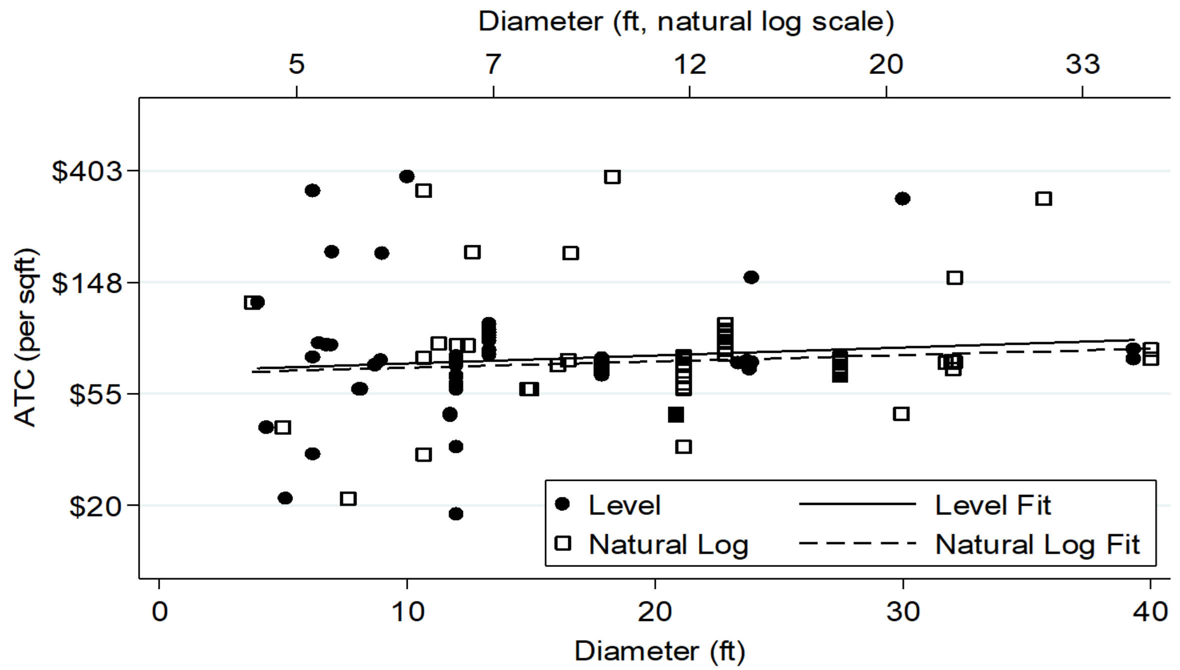


Figure 4-7. Distribution of pipe diameter

Although the log transformation makes the distribution of AW diameter closer to normal, this does not affect the regression coefficient estimates, so is deemed unnecessary. The reason this is the case is highlighted from plotting the relationship between AW diameter and ATC, as shown in Figure 4-8. AW diameter is left in level form as well as plotted under a natural log transformation, with a fitted line shown for each (note the figure has two x-axes). The fitted lines are similar and indicate a slight positive relationship between AW diameter and ATC. The similarity of the fitted lines explain why the regression model is similar regardless of whether AW diameter is left in level form or log-transformed.



Notes: ATC is shown on a natural log scale.

Figure 4-8. Scatterplot for pipe diameter and ATC

The similarity of the fitted lines suggest that a natural log transformation is not needed for AW diameter, which proves to be the case later on when testing various functional forms for the stepwise regression analysis. The fitted lines are also consistent with a priori expectations that increasing pipe diameter might increase ATC, but the relationship does not appear to be very pronounced. For the regression analysis, the effect of diameter on ATC is separated between robotic application and manual application, which proves to be important and indicate that increasing diameter primarily increases the ATC of robotic application, but not necessarily manual application.

Looking at the distribution of AW slope, the mean is 17.94 degrees, the median is 18.65 degrees, and skewness is 0.36. Under a natural log transformation, skewness becomes -1.37. This indicates that AW slope is closer to a normal distribution in level form and that a natural log transformation actually adds skew to the distribution. This is likely because some observations have a slope of zero, which is undefined for a natural log transformation, and some have a positive slope that is less than one, which goes into the negative domain under a natural log transformation. AW slope is therefore left in level form for the regression analysis, which also makes the coefficient estimate more straightforward to interpret (measuring changes in one-degree increments rather than percent changes). Figure 4-9 shows the distribution of AW slope before and after a log transformation, showing that the distribution is closer to normal in level form.

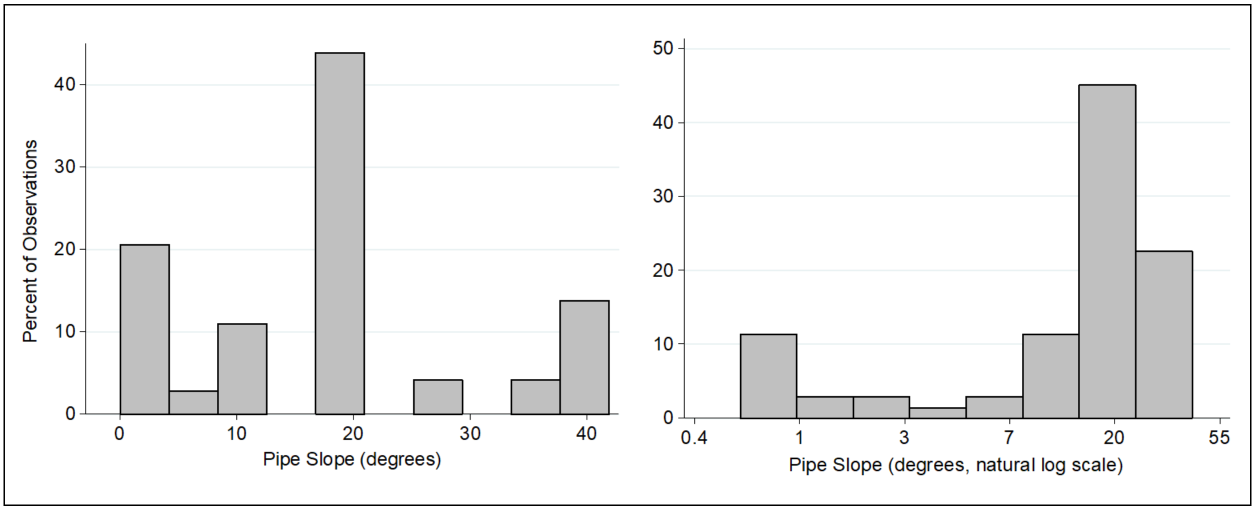
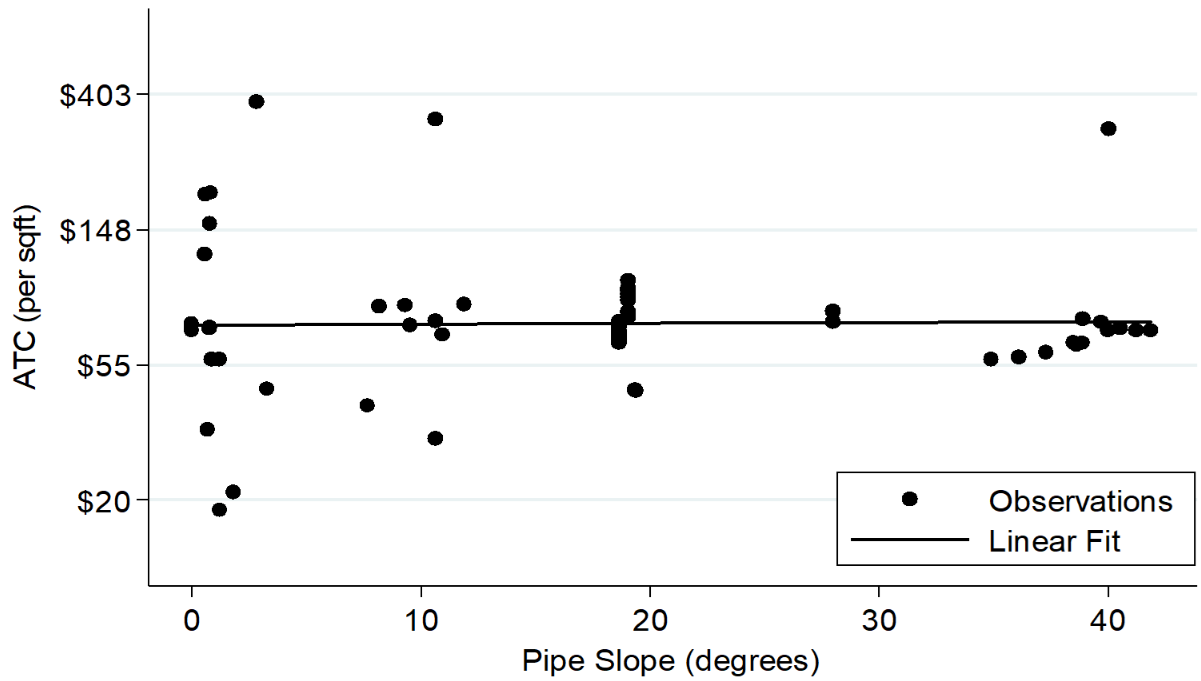


Figure 4-9. Distribution of pipe slope

Figure 4-10 shows a scatterplot between AW slope and the natural log of ATC. There is no obvious relationship between these variables, with only a slight positive slope for the linear fit and more variation in ATC at lower slopes. As done with diameter, the effect of pipe slope is also separated between robotic and manual application for the regression analysis, which again proves to be important. In this case, the results indicate that increasing slope primarily increases the ATC of manual application, but not necessarily robotic application. This means that pipe diameter seems to affect cost for robotic application and pipe slope seems to affect cost for manual application. This is investigated in detail in the stepwise regression analysis (see Appendix A.6).



Notes: ATC is shown on a natural log scale.

Figure 4-10. Scatterplot for pipe slope and ATC

These scatterplots are consistent with a priori expectations that quantity is a key predictor of cost and total relining cost exhibits economies of scale. Furthermore, these figures indicate that a log-log specification is likely necessary to prevent outliers from biasing the estimates, and the figures show that there is a strong log-linear relationship between quantity and ATC. Meanwhile, for pipe diameter and pipe slope it does not appear necessary to use a natural log transformation. Nonetheless, natural log transformations and other functional forms (e.g., polynomial) are explored during the regression analysis, and allowing the impact of diameter and slope to differ for robotic versus manual application proves necessary.

5 Final Regression Model

The final model estimates cost as a function of quantity, ownership, pipe diameter, pipe slope, application type, and location. The model standard errors (SEs) are clustered around facility due to method for collecting and structuring the sample data. The model can be estimated to examine TC or ATC. In a log-log specification, the models provide identical estimates, which is a property of natural logarithms and evaluating percentage changes. Put differently, a percentage change in average cost corresponds with the same percentage change in total cost. The only difference between these models is the coefficient estimate on quantity, while all other variables have identical estimates. The final model with ATC as the dependent variable and with TC as the dependent variable is shown below in Table 5-1. The stepwise regression analysis and robustness checks for the final regression model are detailed in Appendix A.

Table 5-1. Final regression model

Independent Variable	Final Model	
	ln(ATC)	*ln(TC)*
ln(Area Relined)	-0.369*** (0.025)	0.631*** (0.023)
Reclamation Ownership	0.553*** (0.083)	0.553*** (0.062)
AW Diameter	-0.010** (0.004)	-0.010** (0.004)
AW Slope	0.022*** (0.008)	0.022*** (0.008)
*Robotic Application * AW Diameter*	0.030*** (0.008)	0.030*** (0.008)
*Robotic Application * AW Slope*	-0.011* (0.006)	-0.011* (0.006)
Region		
California Great Basin	-0.420*** (0.125)	-0.420*** (0.149)
Columbia Pacific-Northwest	-0.915*** (0.088)	-0.915*** (0.140)
Missouri Basin/Arkansas-Rio Grande-Texas Gulf	-0.624*** (0.081)	-0.624*** (0.133)
Upper Colorado	-0.571*** (0.076)	-0.571*** (0.118)
R-squared	0.9199	0.9784
RMSE	0.149	0.149

Standard errors shown in parenthesis and clustered around facility. Statistical Significance: ***1% Level, **5% Level, *10% Level.

As shown, the final model estimates are identical regardless of using ATC or TC as the dependent variable. The only difference is the estimate on quantity, which now mirrors the other model. More specifically, the ATC model shows that increasing quantity by 100 percent will reduce ATC by 36.9 percent, which is equivalent to saying that doubling quantity will increase TC by 63.1 percent. Meanwhile, the TC model shows that increasing quantity by 100 percent will increase TC by 63.1 percent, which is equivalent to saying that doubling quantity will reduce ATC by 36.9 percent. Both models therefore produce the same estimates for the cost of relining. One notable difference between these specifications is that the model fit is a bit higher with TC as the dependent variable. In particular, R-squared is 0.9784 which means that nearly 98 percent of the variation in TC is explained. That said, RMSE is the same at 0.149, and it is important not to give too much emphasis to R-squared.

A very high R-squared value could actually indicate that the model is overfit and tailored to the idiosyncrasies of the sample, which reduces the generalizability of the coefficient estimates. When fitting a model there is the possibility of "false positives" for coefficient estimates, which is known as a Type 1 error. There is no way to know if a model is overfit, so it is important that the variables have an underlying theoretical reason to be in the model, not just a high statistical significance. It is also important to examine whether the sample is representative and generalizable for the variables of interest. Although new lining type polyurethane was found to be statistically significant, the project team felt the sample was too limited to rely on the coefficient estimate for making predictions, as discussed in Appendix A. This was also a variable without a priori expectations as a key variable for making predictions. Meanwhile, the variables in the final model have a large sample variance and strong theoretical basis for being in the model.

Regression analysis revealed that quantity relined alone explains over 70% of the variation in ATC and 92% of the variation in TC. The high R-squared for the final model is therefore driven primarily by quantity alone, while the remaining variation is explained by the other variables in the model, which capture internal and external features of the relining process. About half of the sample is associated with robotic application and half with manual application, and there is a wide variation in the quantity relined, pipe diameter, and pipe slope. The regional indicators then help to account for time-invariant differences across geographic locations, which could affect cost in various ways, such as the cost of labor and materials. The final model can be written according to Equation 3.

$$\begin{aligned}\ln ATC_{ict} = 7.604 &- 0.369\ln(Q_i) + 0.553(Reclamation_i) - 0.01(AW\ Diameter_i) \\ &+ 0.022(AW\ Slope_i) + 0.03(Robotic_i * AW\ Diameter_i) \\ &- 0.011(Robotic_i * AW\ Slope_i) - 0.420(CGB_i) - 0.915(CPN_i) \\ &- 0.624(MBA_i) - 0.571(UC_i)\end{aligned} \tag{3}$$

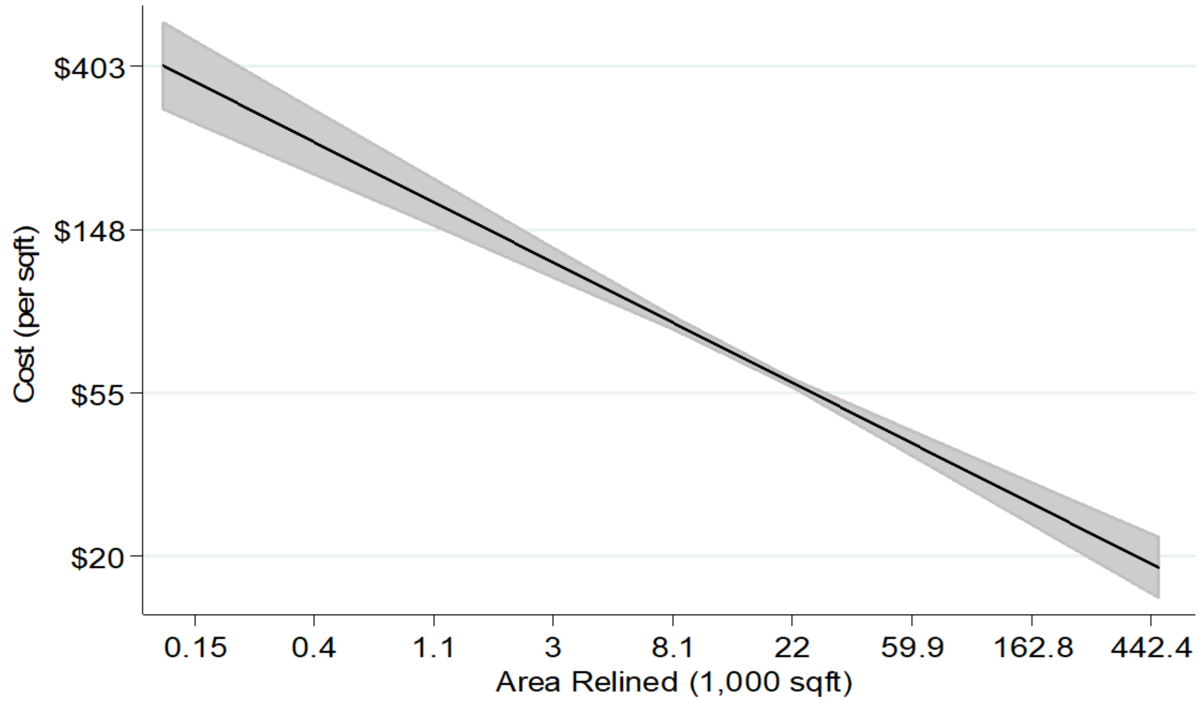
Equation 3 shows that the final model estimates cost as a function of quantity, ownership, pipe diameter, pipe slope, robotic versus manual application, and Reclamation region. Most of the variables are considered external to the lining process, meaning they cannot be chosen and that the model predicts cost based primarily on external factors. The one variable that is internal to the relining process is the choice of robotic versus manual application. For external factors, making predictions is straightforward since these variables are known and data are readily available. Meanwhile, for internal factors assumptions are needed to make predictions, in this case assumptions for which application method will be used in the future.

5.1 Final Model Predictions

To illustrate the predictions produced by the final model, the estimated effects from Equation 3 are shown in the figures below for each variable in the model. These figures indicate the estimated marginal effect on cost from a change in the variable of interest, holding all else equal at the sample means. The estimate for each variable is evaluated across the range found in the sample, including the 95 percent confidence intervals around the model predictions. For all figures shown, the 95 percent confidence interval is based on the delta method and SEs clustered around facility.

The first variable examined is the quantity relined, which is found to be the main driver of cost due to strong economies of scale. ATC is predicted to range from as much as $400 per sqft when relining a few hundred sqft, to as low as $19 per sqft when relining hundreds of thousands of sqft, all else equal. These predictions align with the sample range of $19 to $382 per sqft. This estimated range is likely driven by the underlying fixed costs that contractors face being spread across more area relined, as well as a spreading effect for spending on mobilization, preparation, scaffolding, water control, and hazmat. Spending on these is always required for relining work, and though spending may vary with quantity, it is unlikely to be at a constant rate. It may also be the case that the contractor charges a high markup for relining a small area. Whatever the reason may be for each relining job, the sample and model results indicate strong economies of scale.

Figure 5-1 shows the fitted (predicted) values for quantity relined and average cost per sqft (ATC) across the sample range with the 95 percent confidence interval shown in gray. As expected, the prediction for quantity is most certain around the sample mean and becomes less certain at the extremes. While the model can make predictions beyond the sample range, it is important to realize that this increases the uncertainty range around the predicted value.

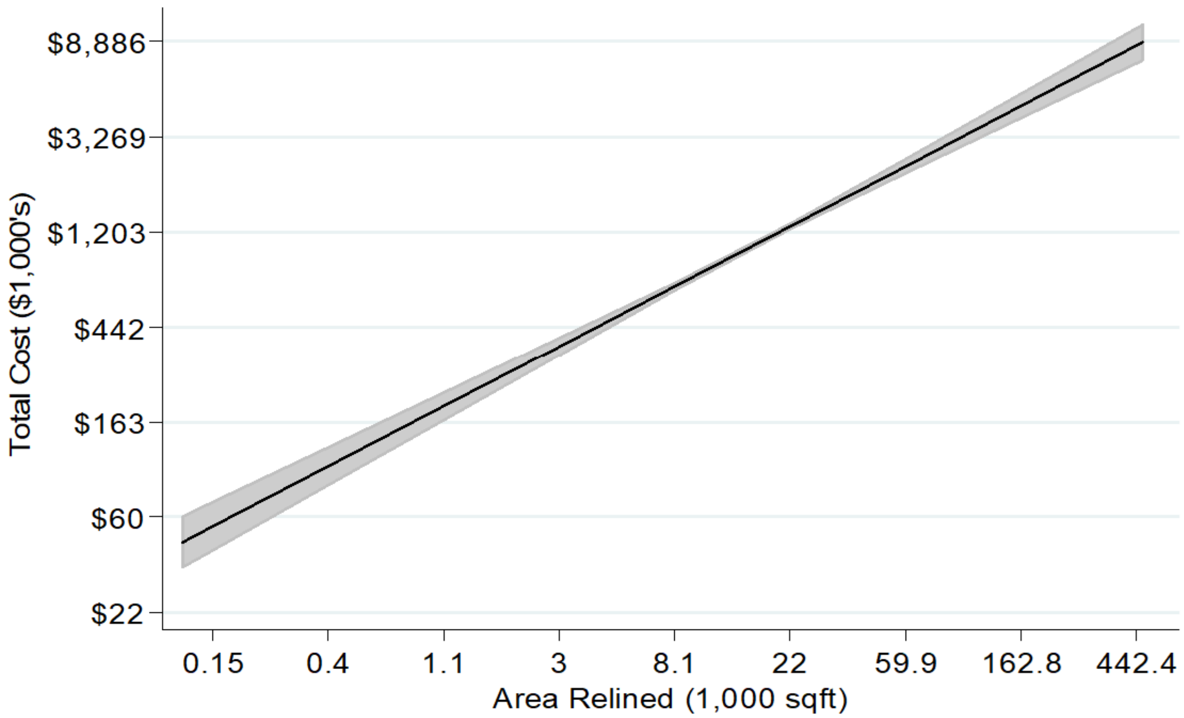


Notes: Cost per sqft (ATC) and quantity are shown on a natural logarithmic scale. The gray area indicates the 95% confidence interval using the delta method and standard errors clustered around facility.

Figure 5-1. Predicted marginal effect for quantity on average cost

As expected from previously visualizing the sample in Figure 4-6, the model predicts a strong log-linear negative relationship between quantity and ATC, indicating economies of scale. Put differently, doubling the quantity relined less than doubles the cost of the overall relining job.

Figure 5-2 shows the fitted line between quantity and total cost on a log-log scale across the sample range, which comes from running the model with TC as the dependent variable, as shown in Table 5-1. This mirrors the result shown in Figure 5-1 for ATC, but instead predicts TC along the y-axis. The model predicts a total cost of around $46,000 when only relining a few hundred sqft and a cost upwards of $8.8 million when relining several hundred thousand sqft, all else equal. This aligns with the sample range of about $44,000-$8.8 million and again emphasizes that quantity is a key predictor of cost.



Notes: Total cost (TC) and quantity are shown on a natural logarithmic scale. The gray area indicates the 95% confidence interval using the delta method and standard errors clustered around facility.

Figure 5-2. Predicted marginal effect for quantity on total cost

The log-linear relationship shown for total cost is expected after previously visualizing the sample on a logarithmic scale in Figure 4-5. Notice that the uncertainty bounds for quantity are fairly tight in both Figure 5-1 and Figure 5-2, which is associated with the high statistical significance on the coefficient estimate for quantity. Other than quantity, the estimates for other variables in the model are identical regardless of whether modeling ATC or TC. This means that the relationships shown in the remaining figures apply equally to both, though attention is placed on ATC reported on the y-axis, as ATC is generally easier to understand and more interesting to examine.

The next variable in the model captures whether the penstock is owned by Reclamation. As reported in Table 5-1, the coefficient on the ownership variable is 0.553. Since the dependent variable is in log form, the coefficient represents the log difference and small incremental changes approximate the percentage change in the dependent variable. However, for a binary variable such as Reclamation ownership, the coefficient represents 100 percent Reclamation ownership versus 0 percent Reclamation ownership. Since it is not possible to look at small incremental changes for a binary variable such as Reclamation ownership, the coefficient is not considered an accurate approximation of the percentage change in the dependent variable. To calculate the change, one must look at the log difference indicated by the coefficient. Holding the other variables at their means, the coefficient estimate indicates that Reclamation pays an average of $79 per sqft, while other entities pay about $46 per sqft relined. In other words, the estimate suggests that Reclamation pays about 72 percent more for relining jobs than non-Reclamation entities in the sample, all else equal.

This result might be driven by several factors, including the proportion of spot repair relining jobs, the area relined per job amongst entities, and any requirements specific to Federal agencies that might not be faced by non-Federal entities.

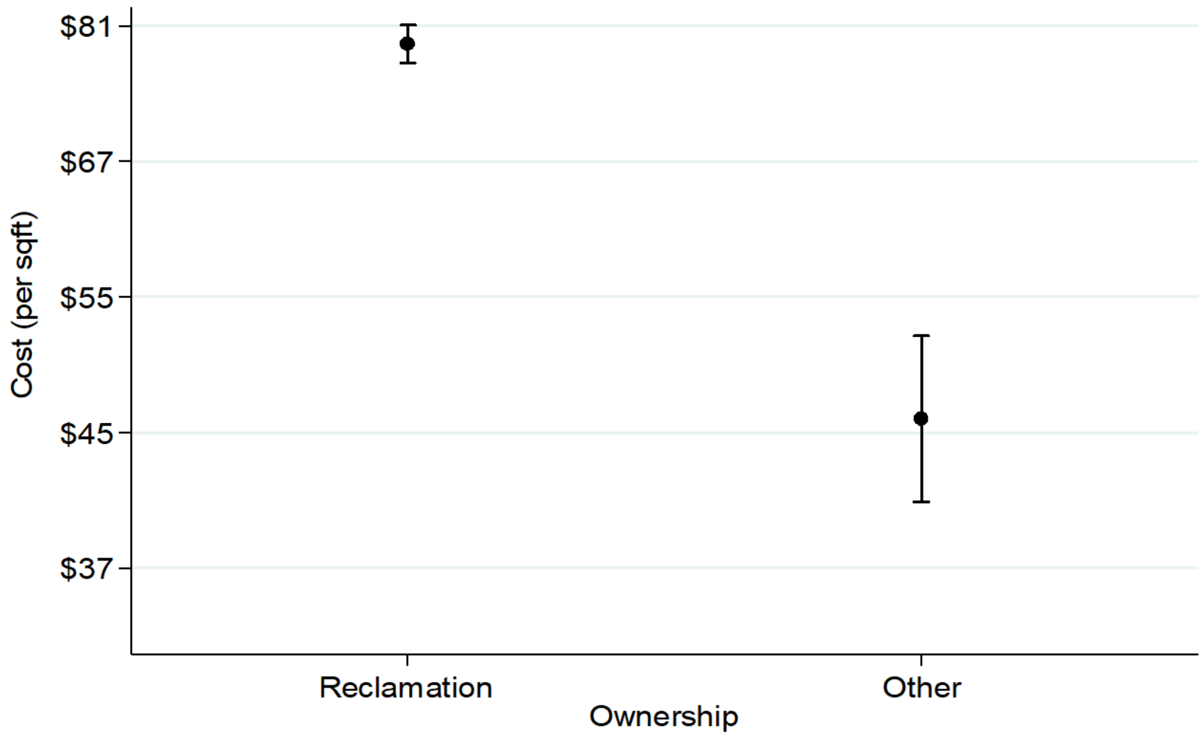
Reclamation is the only entity with spot repair relining jobs represented in the sample data, comprising 22 percent of Reclamation relining job observations. Spot repairs can be an order of magnitude higher unit cost than a full relining for a comparable pipe due to mobilization inefficiencies and fixed costs being spread across a smaller volume of work (see Section 2 for additional details on spot repairs). Relatedly, Reclamation observations have an average repair area per relining job of 15,846 sqft, while for non-Reclamation entities this value is 98,361 sqft—more than six times larger. The model is specified to control for differences in area relined, but the small sample size of non-Reclamation observations might preclude a robust result.

Reclamation is the only Federal agency represented in the sample data. Federal agencies are subject to the Davis-Bacon Act and the Contract Work Hours and Safety Standards Act, as amended, which dictate terms for wages rates and overtime compensation for federally funded contracts.[6] Federal agencies may also specify enhanced safety requirements, such as to stipulate a full-time certified industrial hygienist and certified safety professionals through the duration of the work. It is unknown how (or if) the safety requirements for the non-Federal agencies represented in the sample differ, but such differences could contribute to the relining cost discrepancy.

Lastly, the principal investigators for this study are Reclamation researchers, with an intimate understanding of Reclamation relining job contracts. Each organization has their own means and methods for contracts and the data presentation within. If partner agency relining job contracts were not interpreted in a way that wholly corresponded to the data pulled from Reclamation contracts, some costs may have been overlooked or underestimated. Additional investigation is warranted to uncover what is driving this relining cost difference.

As shown by the 95 percent confidence intervals in Figure 5-3, the uncertainty range is much higher around the cost for other entities relative to Reclamation. This is likely due to the large number of Reclamation observations in the sample.

[6] 4 *Ibid.*

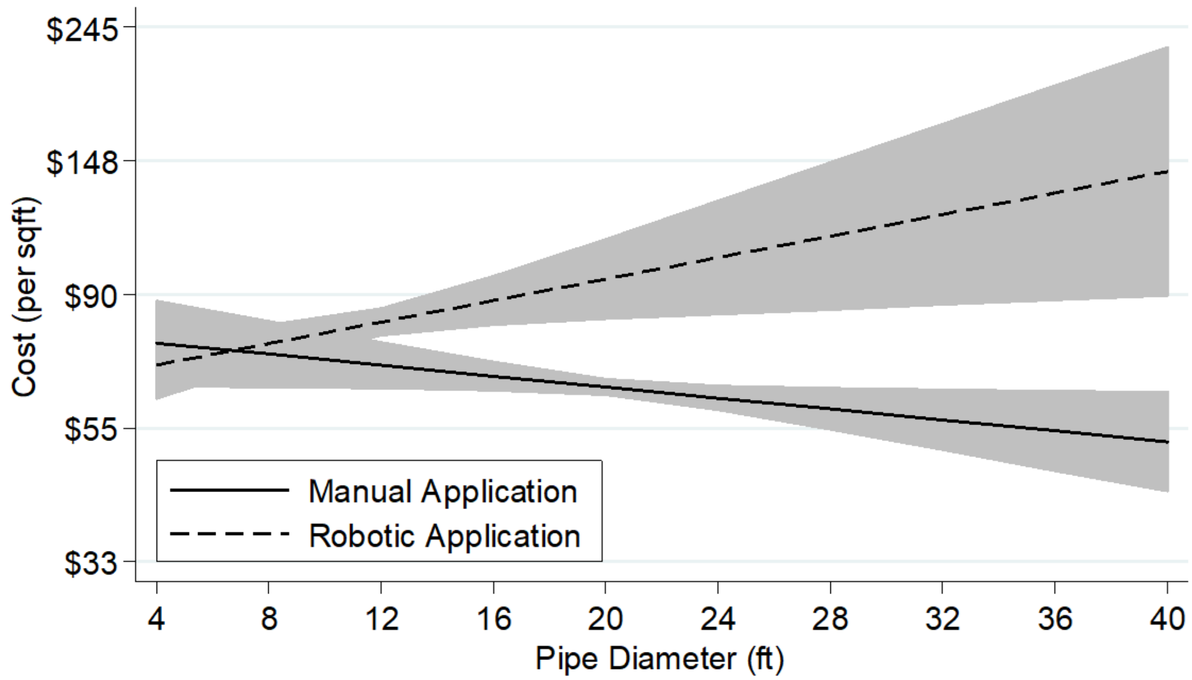


Notes: Cost per sqft (ATC) is shown on a natural logarithmic scale. The lines around the point estimate indicate the 95% confidence interval using the delta method and standard errors clustered around facility.

Figure 5-3. Predicted marginal effect for Reclamation ownership

Ownership is included in Equation 3 as a binary variable. This has the effect of shifting the fitted lines for quantity in Figure 5-1 and Figure 5-2 upward if the pipe is owned by Reclamation. The same applies for the other fitted lines shown below.

The next variable in the model is pipe diameter, which has a varying effect on cost depending on whether robotic or manual application is used. For robotic application, increasing diameter appears to increase cost, while for manual application, cost is higher for a smaller diameter. Robotic application thus appears best suited for small diameter pipes, while manual application is cheaper for large diameter pipes. Figure 5-4 shows the effect of pipe diameter on cost for robotic versus manual application.

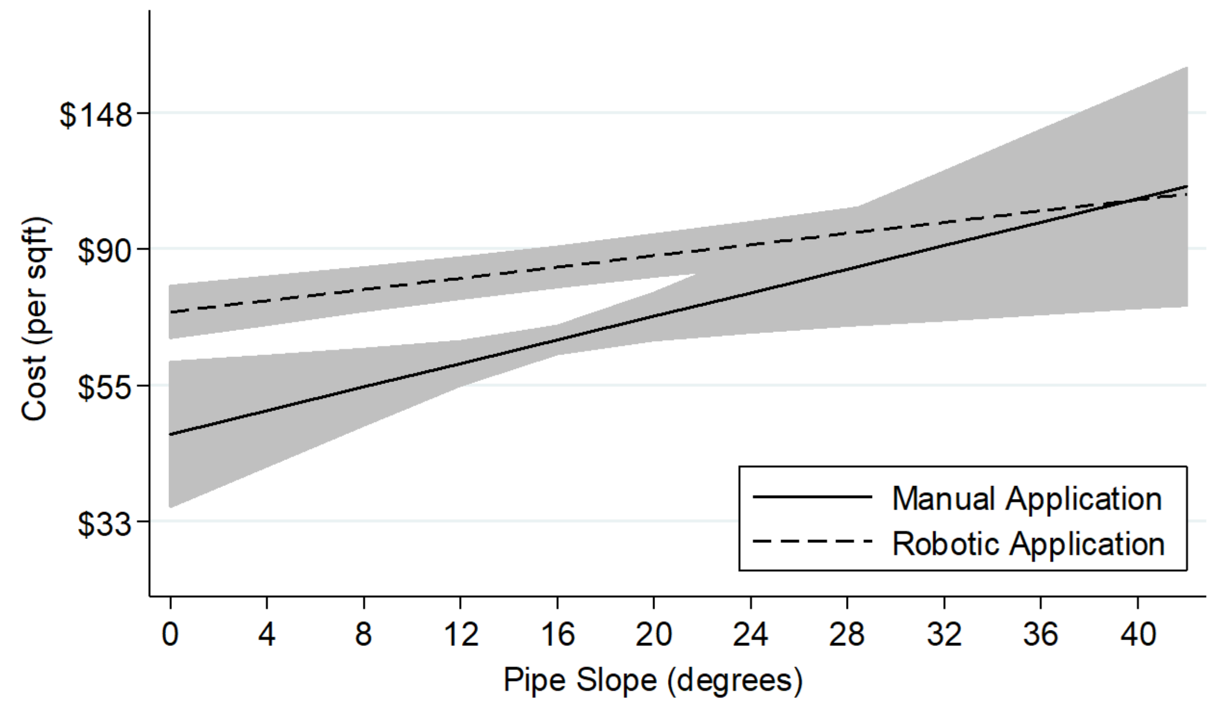


Notes: Cost per sqft (ATC) is shown on a natural logarithmic scale. The gray area indicates the 95% confidence interval using the delta method and standard errors clustered around facility.

Figure 5-4. Predicted marginal effect for pipe diameter, by application type

Figure 5-4 shows that robotic application is on average cheaper than manual application when diameter is small, but the uncertainty range overlaps with manual application, so the difference does appear to be major. For manual application, cost per sqft is about $75 at a 4 ft diameter, decreasing to as low as $52 for a 40 ft diameter. This is likely driven by an increase in access and mobility for equipment and workers as diameter increases, as well as the ability to complete more production at a single location before moving that equipment to the next position along the pipe length. For robotic application, cost per sqft is about $69 at a 4 ft diameter, increasing to as much as $143 for a 40 ft diameter. That said, the uncertainty range gets quite large for robotic application as diameter gets larger, which stems from the fact that the max diameter is 21 ft for robotic application in the sample, which is the largest pipe diameter relined with robotics at the time of this research. It would therefore not be reasonable to use the model to predict the cost of robotic application for very large diameter pipes.

The next variable in the model is pipe slope, which is also modeled as having a different effect on cost depending on whether robotic or manual application is used. The model predicts that manual application is cheaper when pipe slope is low but becomes more expensive as slope increases. Meanwhile, slope has a smaller effect on the cost of robotic application, which converges with the cost of manual application at very steep slopes, all else equal. Figure 5-5 shows the effect of pipe slope on cost for robotic versus manual application.

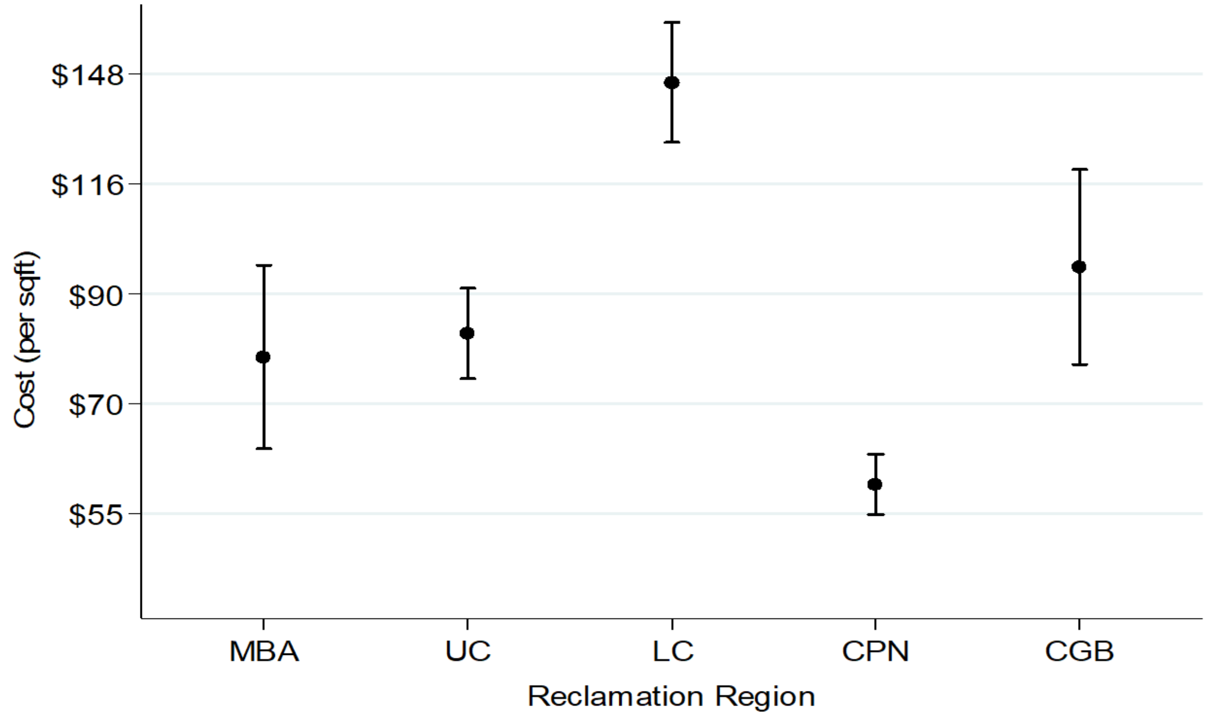


Notes: Cost per sqft (ATC) is shown on a natural logarithmic scale. The gray area indicates the 95% confidence interval using the delta method and standard errors clustered around facility.

Figure 5-5. Predicted marginal effect for pipe slope, by application type

Figure 5-5 shows that the model predicts that manual application is on average cheaper when slope is small, but similar in cost or slightly more expensive than robotic application on steep slopes. For robotic application, cost ranges from about $71 per sqft on no slope to $110 per sqft on a 42-degree slope, all else equal. Meanwhile, for manual application cost ranges from about $46 per sqft on no slope to $113 per sqft on a 42-degree slope, all else equal. Slope therefore has a larger effect on the cost of manual application. This is likely due to the scaffolding and safety equipment needed for manual application on steep slopes, which also requires more time to move along the pipe. Note that the uncertainty range is fairly consistent for robotic application but is fairly large at the extremes for manual application. This is because the sample average for slope is about 23 degrees for robotic application but only 13 degrees for manual application, even though the sample includes observations for both of up to a 40-degree slope.

The final variable in the model is Reclamation region, which was measured using a series of binary variables. Like ownership, regional differences shift the fitted lines shown in the other figures. The model indicates that cost is on average greatest in the LC, followed by (in order of decreasing cost) the CGB, UC, MBA, and CPN. Figure 5-6 shows the average cost predicted for each Reclamation region.



Notes: Cost per sqft (ATC) is shown on a natural logarithmic scale. The gray area indicates the 95% confidence interval using the delta method and standard errors clustered around facility.

Figure 5-6. Predicted marginal effect for Reclamation region

The model predictions for region range from an average cost of $58 per sqft in the CPN Region to $145 in the LC Region. This is likely driven by regional differences in the costs of inputs. These figures show how the model predicts cost across the sample range for each variable in the model, including the range of uncertainty around the predictions.

Overall, the model predicts strong economies of scale, a higher cost for reclamation ownership, varying effects based on location, and varying effects from pipe diameter and pipe slope depending on whether robotic or manual application is used. Robotic application is predicted to be cheaper for small diameter pipes on a steep slope, while manual application is cheaper for large diameter pipes without much incline. This is consistent with observed practices by contractors and makes sense given the challenges associated with using robotic application on large diameter pipes and manual application on steep slopes and small diameter pipes.

5.2 Limitations of Final Regression Model

It is important to understand some of the limitations of the regression model predictions. The first limitation is that the sample used for the regression model may not be representative and generalizable to future relining jobs. This is a concern for any regression analysis, especially when relying on a small sample size. However, the study sample includes nearly all past Reclamation relining jobs and exhibits a wide variance for the variables used in the final model. In light of these considerations, and the use of stepwise regression analysis in model specification, the regression model can confidently be used for making predictions on the dependent variable (relining cost) but offers less confidence in estimating the specific contributions attributable to any specific explanatory variable.

Another possible limitation of the model is associated with making predictions for robotic coating application, with the model distinguishing between robotic or manual application. The results indicate that robotic application is lower cost than manual application for small diameter pipes and pipes on a steep incline. However, robotic application is a technology still being developed, particularly to utilize the technology on increasingly larger diameter pipes. This means future cost savings could be greater than that found for past observations. This also highlights a general limitation of using historic observations to make future predictions. The economic impact of robotic application for relining jobs should continue to be studied as more data becomes available. Possible benefits not captured in this analysis include faster relining jobs—which reduces any opportunity costs associated with the lost hydropower production due to shorter unit outages—and more uniform application. Robotic applications are also thought to increase safety for relining jobs by reducing worker exposure and time within the pipe. Therefore, the possible benefits for robotic application are not entirely economic.

Further, robotic application designation is not explicitly stated in most of the reviewed contracts but, rather, resulted from personal communication with people involved in project execution. Where a knowledgeable person was absent, assumptions about the timing of the work and the contractor involved were used.

The next limitation to keep in mind is that only the variables for which data could be gathered were tested. There are likely other considerations that have an important influence on cost that could not be examined. For example, the project team originally tried to gather information on access to each pipe, looking at the number and size of existing access points. Having sufficient access along the pipe is important because high-pressure material flows from the equipment staged outside the pipe to the worker within the pipe and significant pressure losses can occur at distances greater than several hundred feet. However, access information was not available for most observations, so access could not be tested (see Section 3.2.1). Nonetheless, the analysis found that over 70 percent of the sample variation in ATC and 92 percent of the variation in TC is explained by quantity alone. This means that quantity, along with the other variables in the model, explain most of the sample variation in cost. Even so, the final model error is still about 14.9 percent, which is driven by the remaining unexplained sample variation in cost. This means the model still has room for improvement and additional data and variables could strengthen the model predictions.

Another limitation is that the sample data are based on contract award cost rather than final cost. Final contract costs were available for a limited number of observations and for others the work was not yet completed or not made available. The model therefore predicts the contract award cost. The final contract cost typically includes award cost plus change orders or modifications, which generally add costs. That said, differences between the award and final contract are not expected to have a major influence on the model estimates or predictions.

Lastly, out-of-sample (external) data truthing was not performed because the final regression model was developed using all relining job data available. This maximized the robustness of the model itself but precluded the ability to explicitly test predictive quality.

6 Relining Cost Forecasts

The hedonic cost model shown in Equation 3 offers a way to predict the cost for future large steel pipe relining jobs based on internal and external features of the relining process. Section 6.1 predicts future Reclamation spending on penstock relining, while Section 6.1.3 details the development of a forecasting application for predicting large steel pipe relining costs in general.

6.1 Predicting Future Relining Costs for Reclamation Penstocks

To predict future agency spending on relining, Reclamation's MEPD is used, which includes information for region as well as pipe intake/discharge diameter, intake/discharge elevation, and length. This database contains details for 188 penstocks across 57 facilities that Reclamation manages. After excluding penstocks constituting the study sample (those that were fully relined or spot repaired) and concrete penstocks, 121 steel penstocks remain. Figure 6-1 shows the count and total interior surface area of Reclamation's 121 unrelined penstocks by region.

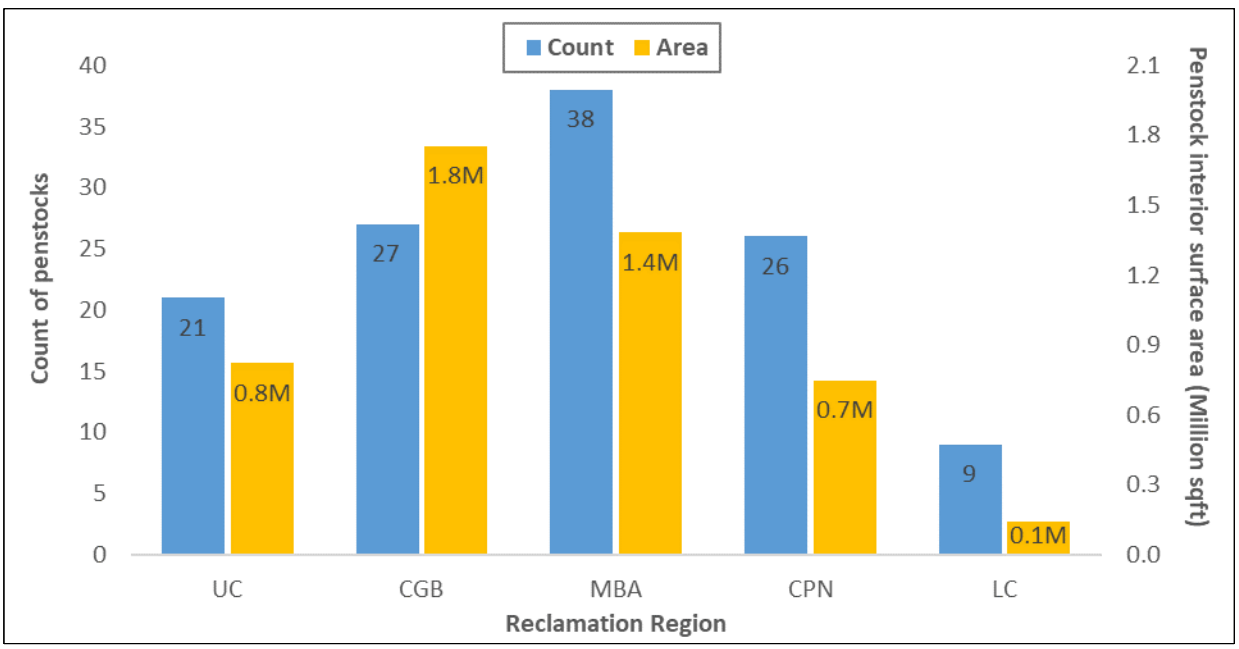


Figure 6-1. Count and total interior surface area of Reclamation's unrelined penstocks by region

It is reasonable to assume that most of these penstocks will need to be relined in the near future, with many of them still relying on the lining from when the facility was first built. Many of these pipes were originally lined with coal tar enamel, which generally has a lifespan of 70 years—the average timespan between penstock installation and relining contract award date for Reclamation penstocks in the study sample. Across these 121 observations, the average lining age is about 63 years, meaning many of these penstocks are due for relining. Figure 6-2 presents the count and age of Reclamation's unrelined penstocks by region, as of 2021.

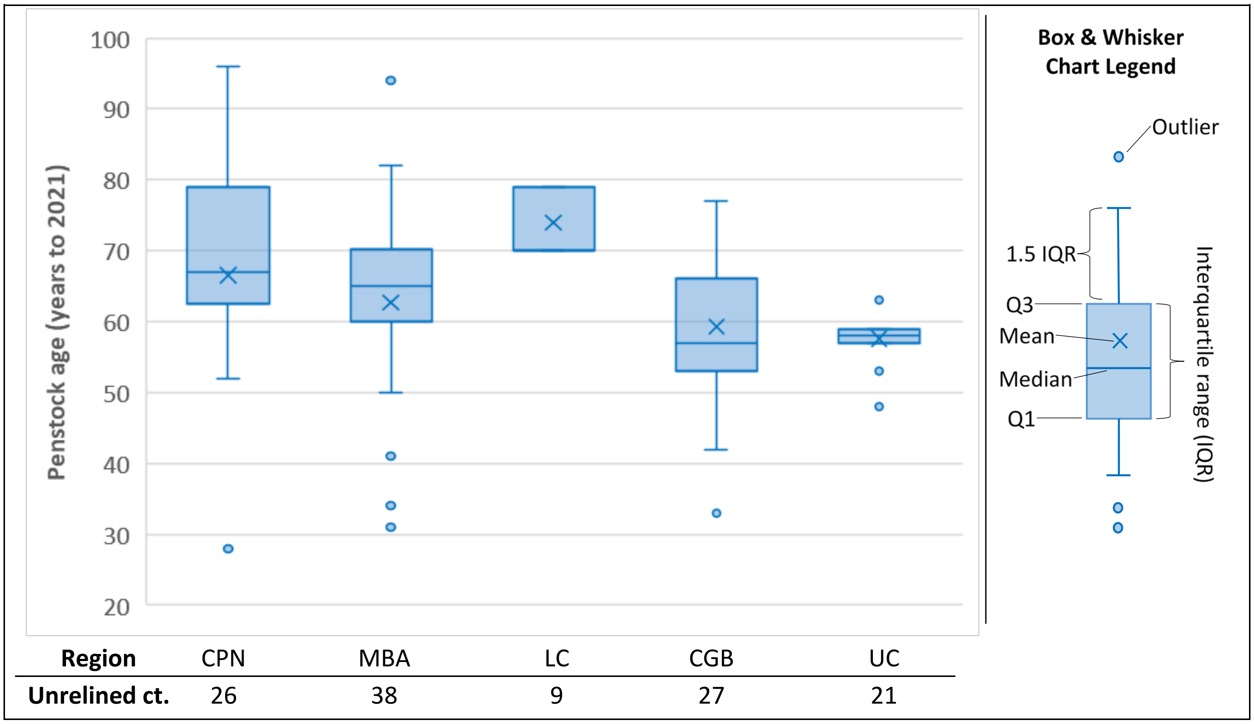


Figure 6-2. Age and count of unrelined Reclamation penstocks (2021 basis) by region

Penstock relining jobs often include the relining of appurtenant features as well. These appurtenances can be large pipe features, such as outlet tubes, or more complex-shaped features, such as draft tubes and scroll cases. Beyond penstocks, Reclamation also manages other large diameter and small diameter steel pipes that require coating maintenance, such as storage reservoir outlet pipes, which are not reported in the MEPD. The area estimates provided in Figure 6-1 are exclusive to Reclamation penstocks that have not been relined or spot repaired (per the records available to the research team), so are necessarily an underestimate of the steel surface area that Reclamation might expect to reline in the coming years.

Sections 6.1.1 and 6.1.2 present two approaches for estimating the future relining costs for the 121 penstocks that are yet to be relined. Section 6.1.1 calculates the cost of relining the 121 penstocks using a lump sum approach—reporting the dollar resource required to reline all penstocks in the current year. Section 6.1.2 calculates the cost of relining the 121 penstocks using a sequential approach—reporting the present value of relining the 121 penstocks over multiple decades.

For both approaches a full reline is assumed for all 121 pipes, but it is reasonable to expect that several spot repairs will also be required for a selection of the penstocks (see Figure 2-3). Due to the exclusion of spot repairs, the costs calculated in the following sections are likely conservative estimates of the actual relining costs. Additionally, the calculations below assume a full reline in a single mobilization, but if a pipe is relined in parts then the cost would be higher due to decreased economies of scale.

6.1.1 Lump Sum Approach

Rather than making assumptions about when relining will be needed for each penstock, and since many are already past due for relining, future spending is calculated assuming all 121 unrelined penstocks in the MEPD will need to be fully relined in the near future. This avoids the need to assume when each penstock will be relined, which depends on the existing lining type, application thickness, pipe use, and frequency of maintenance, most of which is unknown. This also avoids the need to specify a particular time period of analysis. The downside is that values cannot be discounted without knowing when the cost might be incurred in the future. This means that the amount calculated here is undiscounted and reflects the amount that would be needed today to reline all 121 penstocks. This value is reported in 2020$ per the regression model and sample data.

To simplify the calculation, Equation 3 is transformed into a function of only external factors. This is done by plugging in the sample average for application type so that cost is estimated as a function of quantity, pipe diameter, pipe slope, and region which is known for the 121 unrelined penstocks in the MEPD. Given that about half of the sample observations used robotic application, this is equivalent to assuming that about half of future relining jobs will use robotic application and about half manual application. This is reasonable to assume when looking at spending across numerous pipes and aggregating spending. However, for looking at a single pipe relining job, it is not realistic to assume that half of the job is done with robotic application and the other half with manual application. This means that using Equation 3 and assuming either robotic or manual application is the most appropriate way to predict cost for a single relining job.

For predicting future Reclamation spending, using the sample average for application type is deemed the most objective assumption for making predictions. An alternative would be to assume all robotic application or all manual application in the future, but both of these are unlikely scenarios. Another option is to calculate the cost for relining each pipe under both application types and then assume that the cheaper option would be chosen. However, there is no reason to believe that the cheaper option would necessarily be selected, and the choice of application type is largely up to the winning contractor, not necessarily Reclamation. The sample average for application type is therefore plugged into Equation 3 to make predictions based only on external factors. That said, the predicted cost is also reported for using only manual application, using only robotic application, and using whichever option is predicted to be cheaper, highlighting the influence of the application method.

Table 6-1 provides a breakdown of the penstock physical features by Reclamation region for the 121 penstocks evaluated. In total, there is more than 152,000 ft of pipe length and over 4.8 million sqft that will need relining in the near future, with an average pipe diameter of 14 ft and average slope of 10 degrees (both weighted by the area of each pipe). The MBA Region has the largest number of pipes that need relining, but the UC Region has the longest length of pipe and the CGB Region has the most pipe area that needs relining. The LC Region has the fewest number of pipes and smallest area needing relined, but the average pipe diameter is larger than all other areas. Meanwhile, the CPN Region also has a large average pipe diameter, while the UC Region has the steepest pipe slope on average. These features are central to predicting the future spending on relining for each region.

Table 6-1. Penstock physical features by Reclamation region

Region	Number of Penstocks	Total Length (ft)	Total Area (sqft)	Avg Diameter (ft)	Avg Slope (degrees)
California Great Basin	27	37,600	1,752,519	15	7
Columbia Pacific-Northwest	26	20,979	746,083	20	12
Upper Colorado	21	49,239	821,126	9	18
Lower Colorado	9	2,064	142,653	22	7
Missouri Basin/ Arkansas-Rio Grande-Texas Gulf	38	42,596	1,381,659	12	9
Reclamation, All	**121**	**152,478**	**4,844,040**	**14**	**10**

These reflect the 121 penstocks in Reclamation's mechanical equipment database that are assumed to need relining in the near future and used to predict future spending.

To predict future spending for Reclamation, Equation 3 is estimated for each penstock in the database assumed to need relining in the near future (i=1,…,121) and summed to calculate the cost[7] for each region and the agency overall as:

$$Reclamation\ Cost = \sum_{i=1}^{121} \widehat{ATC}_i(Q_i, Z_i) * Q_i \tag{4}$$

Table 6-2 shows the predicted cost for each Reclamation region and the agency overall. The CGB Region has the highest predicted cost at about $77 million and the average unit cost (ATC) is $44 per sqft. This is driven by the large number, long length, and large area of pipe that needs relining, which corresponds with a high TC but relatively low ATC. The MBA Region has the next highest predicted TC at almost $58 million, with an ATC of about $42 per sqft. The UC and CPN regions have the next highest predicted TC, at about $46 million and $30 million, with ATC of $55 and $40 per sqft, respectively. Finally, the LC Region has the lowest predicted TC at about $18 million, but highest ATC at $125, which stems from a lack of economies of scale as well as regional differences. Across all regions, future Reclamation spending on penstock relining is estimated at $228 million.

[7] When using a log transformation, a correction factor is needed to convert the model estimates back to the original untransformed units. This is necessary since data that are close to a normal distribution in log form must be skewed in the original units, which results in a systematic underestimation when the distribution is positively skewed. For predicting Reclamation spending, the correction factor proposed by Baskerville (1972) is used.

Table 6-2. Predicted penstock relining costs by Reclamation region; lump sum approach

Region	Area Needing Relined (sqft)	Average Total Cost ($ per sqft)	Total Cost ($ millions)
California Great Basin	1,752,519	$44.01	$77.13
Columbia Pacific-Northwest	746,083	$40.06	$29.89
Upper Colorado	821,126	$55.44	$45.52
Lower Colorado	142,653	$125.15	$17.85
Missouri Basin/ Arkansas-Rio Grande-Texas Gulf	1,381,659	$41.74	$57.67
Reclamation, All	**4,844,040**	**$47.08**	**$228.06**

Values are 2020$ and total cost is not discounted to reflect when relining might actually occur. Average total cost (ATC) is calculated as total cost (TC) divided by the total area needing relined (Q).

The table includes the ATC for each region as a whole, which ranges from $40 per sqft in the CPN Region to $125 per sqft in the LC Region, with an average of $47 per sqft for the agency overall. This is driven by the size of each pipe in terms of the area needing relined, pipe diameter, and pipe slope, as well as regional differences. Looking across the predicted cost for each penstock, ATC ranges greatly, from as low as $22 per sqft for relining an area in the 100,000's of sqft on no slope, to a max of $321 per sqft for an area of only a few 1,000 sqft and on a steep incline. This is consistent with the range found for the sample observations used for the regression model, which ranged from $19 to $382 per sqft.

Keep in mind that the values in Table 6-2 are calculated at the sample average for robotic versus manual application, with Reclamation expected to spend about $228 million to reline the 121 penstocks evaluated. That said, if only manual application is used, the cost would be about $203 million, and if only robotic application is used, about $260 million. If the cheaper option is chosen for each pipe, meaning robotic application is used for smaller pipes and those on steep inclines, the cost could be as low as $197 million with an ATC of about $41 per sqft. This means that the choice of robotic versus manual application is an important consideration.

To put the predicted future spending on relining into perspective, the relining contracts used for the regression model are examined. For the Reclamation contracts used in the model sample, the total amount for all relining is about $64 million. This reflects a bit over 1 million sqft relined at an ATC of $64 per sqft. This suggests that Reclamation has already started relining some of their more expensive penstocks, and that future relining work should on average entail a lower ATC. On a cost basis, these values suggest that Reclamation has recently addressed a bit more than 20 percent of their total penstock relining needs, with a bit under 80 percent remaining for the near future. The need is even greater on an area basis, with about 4.8 million sqft of area still needing to be relined in the near future, which is more than 80 percent of the penstock area managed by the agency. With roughly about 20 percent of Reclamation's relining needs met on a cost and area basis, it is important for the agency to budget for future relining needs, especially for particular regions and facilities.

6.1.2 Sequential Approach

It is unreasonable to expect that Reclamation would reline all 121 remaining unrelined penstocks within the next year, or even within the next decade. Penstock relining projects compete for many of the same engineering, planning, and budget resources as other Reclamation construction projects. This section was authored in recognition of the typical budget, labor, and prioritization constraints faced by the organization, and models a penstock relining program within the realm of feasibility. Such a program requires prioritization of relining order and spreading of costs over a longer time horizon.

When prioritizing penstock relining decisions, lining deterioration is the intuitive driving factor—i.e., the penstock with the highest degree of lining deterioration should be relined first, the next most deteriorated should be relined second, and so on. Additional factors that might influence prioritization decisions might be critical importance of the penstock (e.g., if it is the only penstock for a facility, it might be prioritized over a similarly deteriorated penstock that is part of a facility with multiple penstocks), and revenue generation capability (e.g., prioritize the penstock that historically contributes to the highest hydropower revenues). In the absence of adequate data to prioritize based on the above-stated factors, this study assumes that penstock lining age is a reasonable proxy for degree of deterioration—i.e., the older the penstock lining, the higher degree of lining deterioration, and therefore the higher priority for relining.

Beyond this basic age prioritization, it is recognized that Reclamation functions as a relatively decentralized organization, with significant budgeting decisions often made at the regional level. Therefore, the sequential approach assumes that each of the five Reclamation regions relines their oldest unrelined penstock each year until all 121 penstocks are relined. The count and age of unrelined penstocks by Reclamation region is reported above in Figure 6-2.

One consequence of this multi-decade approach is that by the time a region has relined all its penstocks, there might be multiple penstocks due (or even past due) for a subsequent relining. This analysis only quantifies the costs of completing the first relining cycle, but the annualized cost serves as a reasonable estimate for the annual dollar resource (reported as present value) required in perpetuity.

This study assumes that such a relining program starts in the current year (2021) and discounts all future relining costs to their present value using the interest rate prescribed for Federal agencies in the formulation and evaluation of plans for water and related land resources for Fiscal Year 2021 (FY2021 Planning Rate) of 2.500 percent (Federal Register, 2020) to account for the time-value of money. The FY2021 Planning Rate is employed as a real discount rate and Reclamation economic analyses therefore report result in real dollars (i.e., there is no assumption of inflation).

Modifying Equation 4 to accommodate the timing element described above for the calculation of present value yields Equation 5. All other modeling specifications stated in Section 6.1.1 are maintained (i.e., Equation 5 is a function of external factors and uses the sample average for application type). Present value of relining costs to a given region is estimated by Equation 5 where i equals one is the region's oldest unrelined penstock and is relined in year t equals one (2021). Penstock i equals I is the region's newest unrelined penstock and is relined in year t equals T. The cost of relining penstock i is discounted over t years at the discount rate r. Note that the MBA Region has 38 penstocks in need of relining—the most of any region—and therefore has a program length of 38 years. Conversely, the LC Region has nine penstocks in need of relining—the least of any region—and therefore has a program length of nine years.

$$PV\left(Cost_{RegX}\right) = \sum_{i=1}^{I}\sum_{t=1}^{T}\frac{\widehat{ATC}_i(Q_i, Z_i) * Q_i}{(1+r)^t} \tag{5}$$

where:

$PV\left(Cost_{RegX}\right)$ = The present value of relining costs to Reclamation Region *X* over the relining program (2021 through year $t = T$)

$\widehat{ATC}_i(Q_i, Z_i)$ = Average total cost of relining penstock *i*

Q_i = Interior area (sqft) of penstock *i*

r = FY2021 Planning Rate of 2.500 percent

t = Year of relining program evaluated ($t = 1, 2, 3, \ldots, T$), where $t = 1$ is 2021 and T is the total duration of the relining program for the region

i = i^{th} oldest unrelined penstock evaluated, where $i = 1$ is the region's oldest unrelined penstock and $i = I$ is the region's newest unrelined penstock

Table 6-3 reports the results of the sequential approach penstock relining program described above, while Figure 6-3 provides a graphical depiction. Program length is reflected by the "year of final reline" column in Table 6-3. The present value of $168 million is an estimate of the total dollar resource required in the current year to accommodate the cost for each relining job in the year it occurs. The equivalent uniform annualized cost (EUAC) of $6.9 million is calculated as the region's present value of relining costs amortized over its relining program duration at the FY2021 Planning Rate and represents the economic cost Reclamation might expect in penstock relining jobs per year.

Table 6-3. Predicted penstock relining costs by Reclamation region; sequential approach

Region	Number of Penstocks	Final Program Year	Avg. area relined per year (sqft)	Present value ($ millions)	Annualized cost ($ millions)
California Great Basin	27	2047	64,908	$58.64	$3.01
Columbia Pacific-Northwest	26	2046	28,696	$20.61	$1.09
Upper Colorado	21	2041	39,101	$36.67	$2.27
Lower Colorado	9	2029	15,850	$16.16	$2.03
Missouri Basin/ Arkansas-Rio Grande-Texas Gulf	38	2058	36,359	$35.78	$1.47
Reclamation, All	**121**			**$167.86**	**$6.89**

These reflect the 121 penstocks in Reclamation's MEPD that are assumed to need relining in the near future and used to predict future spending.

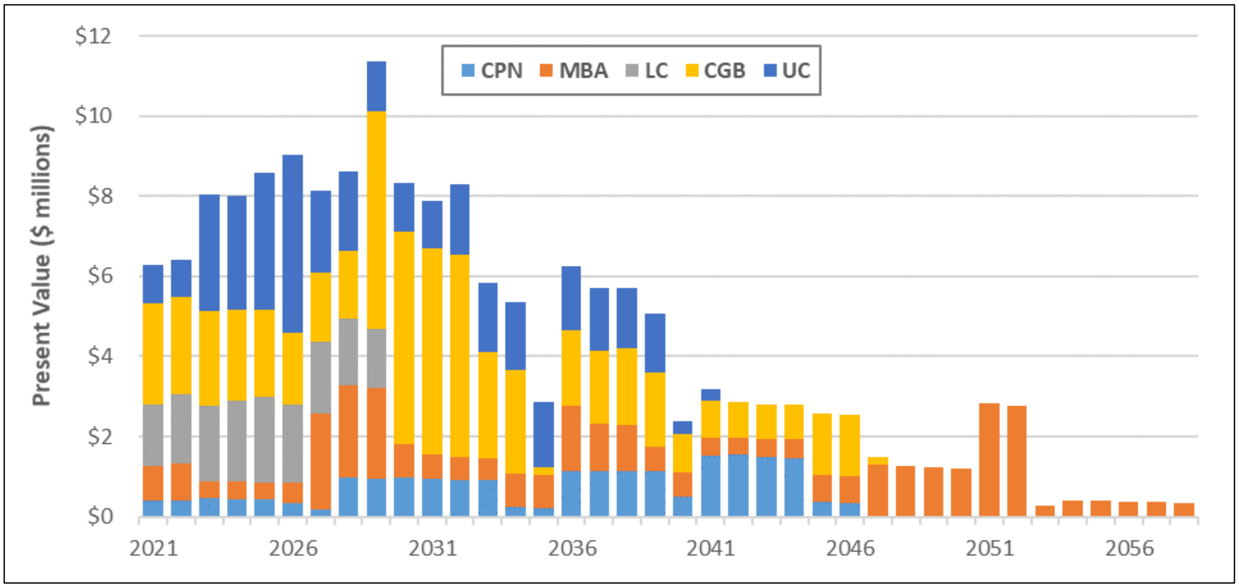


Figure 6-3. Reclamation penstock relining timing and cost using a sequential approach

6.1.3 Limitations of Reclamation Penstock Relining Cost Predictions

It is important to understand some of the limitations of cost predictions based on the regression model, i.e., the estimated future spending for relining jobs. Any limitations of the final regression model (see Section 5.2) are necessarily going to be limitations of relining cost predictions based on the model.

When it comes to the prediction for future Reclamation relining job costs, some additional limitations to the regression model are worth keeping in mind. The first is that the existing lining type, condition, and remaining service life, are mostly unconfirmed for Reclamation's unrelined penstock inventory. Therefore, neither the lump sum approach, nor the sequential approach, is accurately predicting the timing element of future relining jobs, though the sequential approach makes a generalized attempt. The lump sum approach is almost certainly overstating the economic cost for relining all unrelined penstocks (as it does not account for the time value of money), and this might also be the case, to a lesser degree, for the sequential approach. Accounting for the lifecycle of different lining types and knowing when relining might occur would provide a more accurate estimate and allow for improved budgeting insights.

On the other hand, both approaches predict future relining costs based on all penstocks undergoing a full reline in a single mobilization, which necessarily assumes maximum economic efficiency. In reality, some penstocks may be relined in parts, and spot repairs may be needed over time, making the true cost higher than predicted. Coal tar enamel is also no longer used, and the alternative linings used today tend to only have a 30–50-year lifespan, meaning subsequent relines will be needed at shorter intervals.

For multiple reasons, the area relined used in the calculations in sections 6.1.1 and 6.1.2 are necessarily underestimates of the steel surface area that Reclamation can expect to reline in the coming years, which might result in a conservative cost prediction. The prediction is based exclusively on those penstocks reported in the MEPD for which the research team has no record of full relining or spot repairs. Spot-repaired penstocks will likely be due for a full reline sooner than those that have already been fully relined. Reclamation also manages other large diameter pipes that will need relining. For example, the regression model sample includes a few outlet pipes for storage reservoirs. Non-penstock large diameter steel pipes are not reported in the MEPD, and the agency does not currently have a centralized database for these features. The estimate also excludes all small diameter pipes that Reclamation manages.

A final possible limitation arising from the MEPD information is that only unweighted (UW) averages for slope and diameter were possible. Characterizing all penstock physical feature data by LW or AW measures, i.e., by examining penstock drawings akin to Section 3.2, was not feasible. That said, the regression analysis indicated that using the UW, LW, or AW measures had minimal influence on the coefficient estimates (see Appendix A.6). And although AW was used in the final regression model, using UW has minimal influence on the accuracy of predictions.

6.2 App-Based Tool for Predicting Large Steel Pipe Relining Costs

An application-based tool (app tool) was developed based on the results of the final regression model. The app tool requires the user to input the regression model variables. The output is a predicted cost, i.e., forecasted cost, in 2020$.

6.2.1 Purpose and Intended Use

An app-based tool employing the final regression model allows Reclamation and project partners to efficiently leverage the benefits of this research through an intuitive interface. The software utilized for the app-based tool was Microsoft Power Apps, which allows DOI-wide access and use via a shareable link. A subsequently developed Microsoft Excel spreadsheet tool also incorporates the final regression model for sharing with the non-DOI project partners and as requested. The tools are identical in their input requirements, treatment of the inputs, and calculation of results.

The app tool predicts relining job costs using the coefficients and standard errors from the final regression model specified in Section 5. The tool is in no way a replacement for formal cost estimates. The results of the app tool should be considered preliminary investigation into the possible range of relining job costs for any given project.

6.2.2 Features

The Microsoft Power Apps and Microsoft Excel tools feature a simplistic, interactive user interface. To predict relining job costs, the user must provide inputs for each of the following:

- The total surface area being relined.
- The average diameter and average slope of the large pipe feature being relined.
- Whether the contract is a Reclamation relining job or a contract for some other agency or organization.
- Whether or not the contractor will use robotic technologies for significant aspects of the project; if not known, develop cost predictions for both options: Yes and No.

- The region where the pipe is located, selecting from Reclamation regions shown in the app-provided region map.

The user selects "Calculate" after entering inputs for each variable, revealing the predicted cost in 2020$. The results are given in both total cost and cost per sqft. The total cost is a prediction for the coating-related aspects of the relining job, and the cost per sqft is the respective unit cost. The app tool also provides a 95 percent confidence interval for the predicted costs. An image of the current version of the app tool is provided in Figure 6-4.

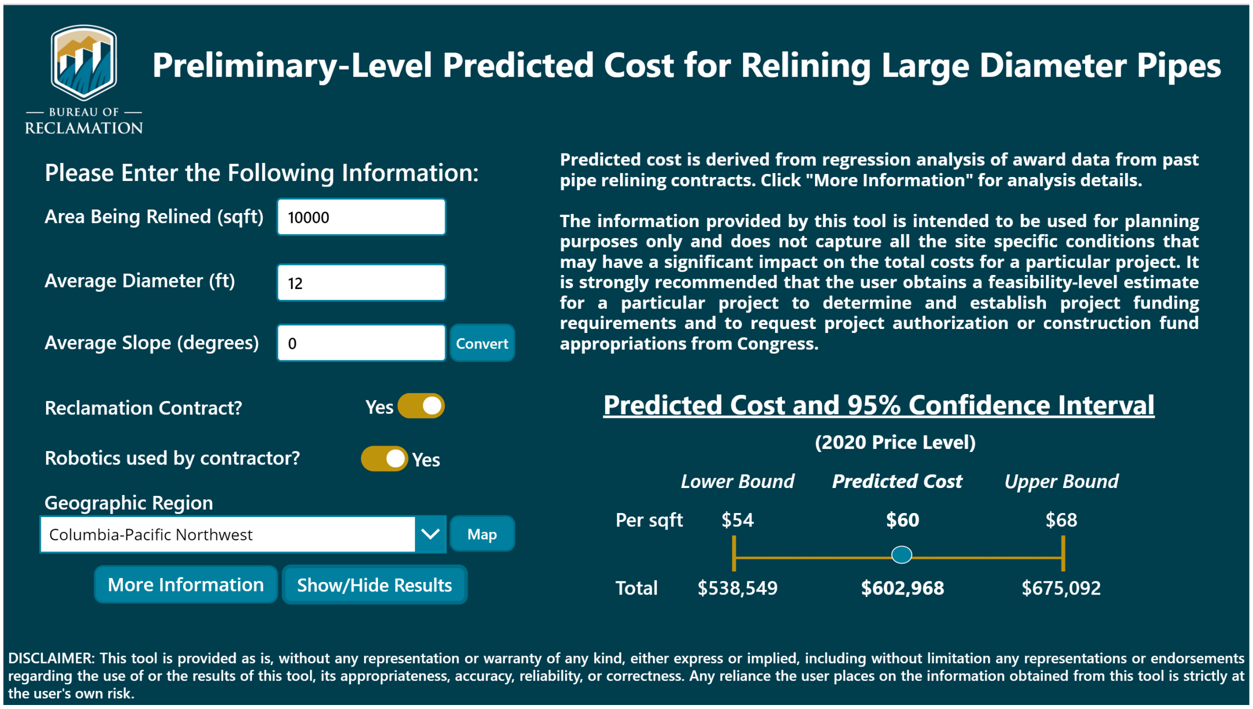


Figure 6-4. Screenshot of Microsoft Power Apps app tool for predicting large steel pipe relining costs

Additional features of the app tool provide user guidance, unit conversion tools, and background information for improved user comprehension. For example, the application provides graphics to assist in converting the slope of the pipe to degrees and to identify the Reclamation region of the pipe's location. There is also a link to a "More Information" page containing instructions and a link to the final research report.

DOI users can access the app tool at: https://apps.gov.powerapps.us/play/b693bfe3-6ec7-47ed-b5d7-eff742f97b53?tenantId=0693b5ba-4b18-4d7b-9341-f32f400a5494.

6.2.3 Limitations of Cost Predictions Made by the App-Tool

Any limitations of the final regression model (see Section 5.2) are necessarily going to be limitations of relining cost predictions based on the model. Additional limitations, specific to the app-tool, are discussed here.

One possible limitation to reiterate is that the app-tool, like the cost predictions in Section 6.1, uses UW averages for slope and diameter. Using LW or AW measures of slope or diameter had slightly higher statistical significance in the final regression model, but using UW has minimal influence on the accuracy of predictions.

Another possible limitation is that the app tool applies a final regression model that is based largely on Reclamation relining jobs. Although every attempt was made to ensure broadly applicable results, cost variations can occur between public and private agencies or even between Reclamation and other Federal agencies. Influence from this possible limitation is particularly likely if the user-defined relining job has characteristics notably different from those in the study sample. Possible examples are for relining jobs outside of the United States or for non-water purposes, such as oil and gas, as all relining jobs in the study sample were performed in the United States for water-carrying large pipes.

Finally, it is important to re-emphasize that cost predictions generated with the app tool are not a substitute for formal cost estimates for specific relining jobs. The structural approach taken in tailored cost estimates, in accordance with Reclamation Policy, Directives and Standards, and various guidelines, reflects a specific relining job. In contrast, the app tool cost predictions are based on this study's sample data of 73 observations and offers only an expedient cost prediction.

7 Conclusions

The two primary research objectives of this work were to identify the major cost drivers for large pipe interior protective coating contracts, i.e., relining jobs, and to specify a final regression model to estimate future corrosion protection costs. The conclusions drawn from this research are presented below.

7.1 Cost Drivers Identified for Large Pipe Relining Projects

The econometric analysis employed regression analysis for 73 observations developed from multiple relining job award contracts. The following preliminary conclusions could be drawn from these results:

- Quantity relined is found to be the main driver of total relining cost and a main driver of unit cost due to strong economies of scale.
- The effect of pipe diameter on cost is dependent on whether application is manual or robotic.
- The effect of pipe slope on cost is dependent on whether application is manual or robotic.
- The model indicates that geographic region has a significant effect on relining cost.
- There is a significant, and pronounced, interagency effect on relining unit cost.

Quantity relined is found to be the main driver of total relining cost. Additionally, quantity relined is found to be the main driver of unit cost due to economies of scale. ATC is predicted to range from as much as $400 per sqft when the relining job is a spot repair of a few hundred sqft, to as low as $19 per sqft when the relining job is a full removal and replacement of hundreds of thousands of sqft, all else equal. These predictions align with the sample range of $19-$382 per sqft. The economies of scale are likely driven by the underlying fixed-cost that contracts face being spread across more area relined, as well as a spreading effect for spending on mobilization, preparation, scaffolding, water control, and hazmat.

The researchers hypothesized that large pipe physical dimensions, namely diameter and slope, are significant drivers of relining costs, with unit costs increasing with steeper grades and larger diameters. Additionally, it was hypothesized that the use of robotics leads to lower unit costs. The findings indicate that diameter and slope interact with robotic application in ways that partially support these hypotheses.

The effect of pipe diameter on cost is dependent on whether application is manual or robotic. For robotic application, increasing diameter increases cost, while for manual application, cost is higher for a smaller diameter. For manual application, cost per sqft is about $75 at a 4 ft diameter, decreasing to as low as $52 for a 40 ft diameter. This might be driven by improved access and mobility for equipment and workers as diameter increases as well as the ability to complete more production at a single location before moving that equipment to the next position along the pipe length. For robotic application, cost per sqft is about $69 at a 4 ft diameter, increasing to as much as $143 for a 40 ft diameter.

Like diameter, the effect of pipe slope on cost is dependent on whether application is manual or robotic. The model predicts that manual application is cheaper when pipe slope is low but becomes more expensive as slope increases. Meanwhile, slope has a smaller effect on the cost of robotic application, which converges with the cost of manual application at very steep slopes, all else equal. For robotic application, cost ranges from $71 per sqft on no slope to $110 per sqft on a 42-degree slope, all else equal. Meanwhile, for manual application cost ranges from $46 per sqft on no slope to $113 per sqft on a 42-degree slope, all else equal. Slope therefore has a larger effect on the cost of manual application—perhaps due to the scaffolding and safety equipment needed for manual application on steep slopes, which also requires more time to move along the pipe.

The model indicates that Reclamation region has a significant effect on relining cost, with unit cost being the highest in the LC Region, followed by (in order of decreasing cost) the CGB, UC, MBA, and CPN regions. The model predictions for region range from an average cost of $58 per sqft in the CPN Region to $145 per sqft in the LC Region. The inter-regional relining unit cost differences might be driven by regional differences in input costs.

Lastly, results indicate a significant interagency difference in relining unit cost. Specifically, Reclamation relining costs are 72 percent higher than non-Reclamation agencies represented in the sample, all else equal. When other variables in the model are held constant at their means, the estimated difference translates into Reclamation paying an average of $79 per sqft, while other entities pay about $46 per sqft relined. Possible reasons might include interagency differences in selection of project delivery method, wage rate constraints specific to Federal agencies (the non-Reclamation agencies are all non-Federal), and the proportion of spot repair relining jobs (Reclamation has the only spot repair relining jobs represented in the study sample). An additional consideration is the potential for lack of consistency across cost items included in the Reclamation versus non-Reclamation observations, due to differing language conventions, line-item cost aggregation, or other factors. The uncertainty range is much higher around the cost for other entities relative to Reclamation—likely due to the large number of Reclamation observations in the sample. An expanded investigation that includes an increased sample size for non-Reclamation agencies could help to confirm magnitude and cause of the observed interagency difference in relining unit cost.

A discussion on the limitations for each analysis and approach is included in the main body of the report. These considerations provide both transparency and enhanced understanding in interpreting the research results and conclusions.

7.2 Future Relining Cost Predictions

The hedonic cost model developed for this work offers a way to predict the cost for Reclamation to reline other large steel pipes in the future based on internal and external features of the relining process. The model was applied to the 121 Reclamation steel penstocks not in the study sample, i.e., that are likely to be relined in the future, using two approaches: lump sum and sequential. The estimates under both approaches evaluate only a complete relining, i.e., total coating removal and replacement. The estimates exclude the relining of penstock appurtenant features, non-penstock steel pipes that require coating maintenance, and the cost of intermittent spot repairs that might occur before a full reline. Therefore, results reported are conservative estimates of the actual relining costs the agency should anticipate. Table 7-1 summarizes the results of the two approaches.

The lump sum approach does not assume when the relining will occur, resulting in an undiscounted cost and simplification of the calculation. By this approach and its underlying assumptions, the CGB Region has the highest predicted cost at about $77 million, with a unit cost (ATC) of $44 per sqft. This is driven by the large number, long length, and large area of pipe that needs relining, which corresponds with a high TC but relatively low ATC. The MBA Region has the next highest predicted TC at almost $58 million, with an ATC of about $42 per sqft. The UC and CPN regions have the next highest predicted TC, at about $46 million and $30 million, with ATC of $55 and $40 per sqft, respectively. Finally, the LC Region has the lowest predicted TC at about $18 million, but highest ATC at $125 per sqft, which stems from a lack of economies of scale as well as regional differences. Across all regions, future Reclamation spending on penstock relining is estimated at $228 million.

The sequential approach, by contrast, develops the assumption that the timing of future relining is one penstock per region per year, by order of oldest-to-newest unrelined penstock within each region. This approach attempts to account for the reality that penstock relining jobs compete for many of the same personnel and budgetary resources as other Reclamation construction projects. Further, it discounts the cost of future relining work to its present value. The agency-wide cost of relining the 121 penstocks is a present value of approximately $168 million (discounted using the Federal Planning Rate of 2.500 percent), or an EUAC of $6.9 million—the economic cost Reclamation might expect for penstock relining jobs per year over the 38-year relining program.

The MBA Region has 38 penstocks in need of relining—the most of any region—and therefore has a program length of 38 years. The present value of relining these penstocks over 38 years is approximately $36 million, or an annualized cost of about $1.5 million. Conversely, the LC Region has nine penstocks in need of relining—the least of any region—and therefore has a program length of nine years. The present value of relining these penstocks over nine years is approximately $16 million, or an annualized cost of about $2.0 million. The CGB region has the highest present value of relining costs at nearly $59 million, followed by (in order of decreasing cost) the UC, MBA, CPN, and LC regions. The CGB region also has the highest annualized cost, at over $3.0 million, followed by (in order of decreasing cost) the UC, LC, MBA, and CPN regions.

Table 7-1. Summary results for two approaches predicting penstock relining costs by Reclamation region

Region	Lump Sum Approach[a]		Sequential Approach[b]			
	Sqft relined in current yr	Total cost ($ millions)	Relining prog. duration (yrs)	Avg. sqft relined per yr	Present value ($ millions)	Annualized cost ($ millions)
CGB	1,752,519	$77.13	27	64,908	$58.64	$3.01
CPN	746,083	$29.89	26	28,696	$20.61	$1.09
UC	821,126	$45.52	21	39,101	$36.67	$2.27
LC	142,653	$17.85	9	15,850	$16.16	$2.03
MBA	1,381,659	$57.67	38	36,359	$35.78	$1.47
Agency total	**4,844,040**	**$228.06**	**38**		**$167.86**	**$6.89**

[a] Assumes relining of 121 unrelined Reclamation penstocks. Values are 2020$ and total cost is not discounted to reflect when relining might occur. See Section 6.1.1 for additional details.

[b] Assumes relining of 121 unrelined Reclamation penstocks in order of oldest to newest, by region, at a rate of one penstock relined per region per year. Relining program discounts all future relining costs to their present value using the FY2021 Planning Rate of 2.500%. See Section 6.1.2 for additional details.

The application of robotics to large diameter pipe relining is a technology still being developed, meaning future cost savings could be greater than that found for past observations. This highlights a general limitation of using historic observations to make future predictions.

7.3 Unanswered Research Questions and Untested Hypotheses

A secondary research objective was to determine the economic break-even point for performing spot repairs (as a percentage of total interior surface area) versus a full reline. However, the dataset did not contain sufficiently varied observations for spot repair and full relining for the model to determine this break-even point. As additional relining job data become available, the model can be updated to support this evaluation.

The research failed to conclusively support or refute two of the hypotheses posited in Section 2.2. It was hypothesized that relining unit costs have increased over time in real dollars due to multiple factors, including safety regulations, environmental regulations, and escalating construction costs (beyond the rate of inflation). The data evaluated spanned the years 1999–2020, but was heavily skewed at the upper end, with an average award year of 2017. The insufficient variability in award year did not allow us to test this hypothesis.

Second, the team hypothesized that more complex jobs would have a greater discrepancy between contract award cost and final cost. As described in Section 3.1.1, the research team identified three general categories of relining job complexity in the data acquisition and aggregation phase. Most of the 73 award cost observations could be clearly assigned to one of these categories, but only 16 final cost observations were developed in total—an insufficient number to robustly test the effect of relining job complexity on the difference between award and final cost. The limited number of final cost observations due to awarded relining jobs that are not yet completed, and in some cases the work has been completed but final data was not made available to the research team.

Out-of-sample (external) data truthing was not performed because the final regression model was developed using all relining job data available. This maximized the robustness of the model itself but precluded the ability to explicitly test predictive quality.

8 Recommendation for Next Steps

- Update the observation dataset and regression model at regular intervals. A suggested interval is annually, or as relining jobs become available.
- Perform out-of-sample truthing to evaluate the regression model's predictive quality, i.e., predict on relining job award data not used in model development and compare to the actual award cost.
- Develop a model comparing award versus final contract data. Additional final contract data for relining jobs are needed to complete this work. The cost difference or percent difference is a likely dependent variable in the analysis.
- Expand sample size to increase proportion of non-Reclamation agencies to explore and better explain the observed interagency difference in relining unit cost.
- Investigate in detail the cost-effectiveness of robotics usage for relining work. Potential benefits might include faster production rates, a higher quality product, lesser labor expenditures and waste, and improved worker safety. Associated costs might include capital investment, operation, and maintenance costs for specialized equipment, specialized training costs, and potential delays due to emerging technology issues (e.g., calibration, sensors, etc.). Additional considerations should be given to the ongoing development of robotics technology, which are converting from manned platforms to autonomous platforms, i.e., no workers required inside the penstock. Such an analysis should be revisited regularly considering the rapid evolution and adoption of this technology.
- Determine the economic break-even point for full relining versus spot repair. The analysis would identify the percentage of lining degradation (as a proportion of total interior surface area) where it is more cost-effective to perform a full reline rather than spot repairs. Evaluate possible factors driving the break-even point and add this output to the app tool to aid coatings specialists and facility staff.

- Evaluate the effect of feature accessibility, i.e., the ease of access for mobilizing relining equipment and personnel to appropriate locations within the pipe. Determine the most appropriate variables for testing. Variables considered but not used in this study were number of access points, distance between access points, and access point size.
- Perform a benefit-cost analysis of not relining large diameters pipes, such as penstocks. If focused specifically on penstocks, investigate case histories of facilities, anticipated to be outside of Reclamation, where lack of coating maintenance resulted in a unit shutdown.

9 Project Data

- Share Drive folder name and path where data are stored: T:\Jobs\DO_NonFeature\Science and Technology\2018-PRG-Econometric Corrosion Cost Model
- Point of Contact name, email, and phone: Bobbi Jo Merten, bmerten@usbr.gov, 303-445-2380
- Short description of the data: Project data files and database, final regression model data, Microsoft Power Apps predicted cost app tool (MSAPP), Microsoft Excel predicted cost spreadsheet tool, app tool guide and update guides.
- Microsoft Power Apps-based app tool, "Preliminary-Level Cost Prediction for Relining Large Diameter Pipe available to all DOI users at: https://apps.gov.powerapps.us/play/b693bfe3-6ec7-47ed-b5d7-eff742f97b53?tenantId=0693b5ba-4b18-4d7b-9341-f32f400a5494
- Keywords: Cost of corrosion, econometric analysis, regression model, penstock, pipe, coating, relining, maintenance planning, predicting cost
- Approximate total size of all files: 1.5 GB

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Appendices

Appendix A. Stepwise Regression Analysis
Appendix B. Relining Job Data Item Description Tables

Appendix A. Stepwise Regression Analysis

A.1 Stepwise Regression Analysis Overview

Stepwise regression is exploratory and involves a step-by-step iterative construction of a regression model through a structured process of testing and selecting variables. This entails adding or removing potential variables after each iteration to test for statistical significance. In general, the goal is to obtain the highest model fit using the fewest number of variables.

Approaches to stepwise regression include forward selection, backward elimination, and bidirectional. Forward selection involves testing the addition of new variables, backward elimination involves starting with all candidate variables and testing the deletion of each variable, and a bidirectional approach is one that uses a combination of adding and deleting variables. This work primarily employed forward selection. However, as some variables were added, others were sometimes removed, meaning the analysis is overall bidirectional. The final regression model is selected based on the highest model fit using the fewest number of variables that are statistically significant. The candidate variables and hypotheses tested are limited by the data available. Reliance on historic contract data means that only certain variables and hypotheses could be explored.

To help inform the stepwise regression analysis, the data are first summarized for candidate variables and a priori expectations are discussed to establish the theoretical basis for testing each variable. This helps to guide the stepwise analysis and highlight some of the most appropriate functional forms to test.

A.2 Rationale for Stepwise Regression Analysis

To estimate the hedonic cost function that was shown in Equation 1, a stepwise regression analysis is performed primarily using forward selection and testing each variable of interest. A stepwise analysis generally aims to achieve the best model fit (typically measured by R-squared) using the fewest number of variables that are statistically significant for predicting the dependent variable of interest (in this case cost). The modeling is limited to the variables that the project team was able to obtain data for and that was consistent across historic observations. Variables are tested independently and together using various functional forms (level, quadratic, logarithmic, and interactions) to determine the final regression model specification that provides the most accurate predictions. Ordinary least squares (OLS) regression is used, which estimates a linear equation while minimizing the model residuals, which reflect the difference between the observed values and predicted values.

To guide the regression specifications that need to be tested, insights are used from the section examining the descriptive statistics and scatterplots for the variables of interest. Various regression specification tests are also performed. For ease of understanding, only certain models get reported, which are primarily those that provide the most insight and inform the final model specification. Other models and insights are also discussed, but the results are not always reported. This is generally due to a lack of statistical significance, small coefficient magnitude, small impact on overall model fit (R-squared), high multicollinearity with other variables, or a combination of these factors.

Regressions are grouped according to the variables of interest to show how the variables are selected and modeled in the final model specification. The first set of regressions focus on quantity, followed by regressions looking at location, time, and ownership, regressions looking at pipe physical features, regressions looking at lining types, and finally, regressions looking at application type. The stepwise analysis is presented in a fairly linear manner, but note that various orderings were explored, and the analysis repeatedly narrowed the regression model down to the same final model speciation.

After identifying the final model specification, several robustness checks are performed, and the model predictions are examined in detail before making predictions of future Reclamation spending on relining. As shown later on, the specification used for the final model provides identical estimates regardless of whether TC or ATC is modeled as the dependent variable, which arises due to the properties of natural log transformations. The stepwise analysis therefore focuses on predicting ATC according to Equation 1, and TC is calculated by multiplying the predicted ATC by quantity, as shown in Equation 2.

Note that all regressions shown for the stepwise analysis report the heteroscedastic-robust standard errors (SEs), which reflects an adjustment to SEs to account for potential heteroscedasticity (non-constant variance in the model residuals). Heteroscedasticity is common in cross-sectional regression analysis and adjusting for heteroscedasticity does not affect the magnitude of coefficient estimates, only the statistical significance of those estimates. There is no downside to adjusting for possible heteroscedasticity, so best practice is to generally report the heteroscedastic-robust SEs (referred to as the robust SEs from here on). As shown later when examining the residuals for the final model and running various tests for heteroscedasticity, this adjustment is necessary. Clustered SEs are also explored later when examining the robustness of the final model.

A.3 Limitations of Stepwise Regression Analysis

Stepwise regression analysis is an efficient and systematic approach for investigating topics where previous work is scant or nonexistent. However, it is not based primarily on theoretical justification, and therefore it is susceptible to bias and poor fit outside the sample used for modeling and must be employed judiciously. Stepwise regression analysis is especially useful when the primary purpose of the model is to estimate the dependent variable (in this case, relining cost), but can be less reliable for evaluating the effect of specific explanatory variables (e.g., pipe diameter).

The stepwise regression approach used was bi-directional, though primarily employed forward selection. There are some potential issues that can occur with forward stepwise regression that should be acknowledged:

- Potential to underestimate certain combinations of variables due to selection order.
- Potential for suppressor effects, which occur when explanatory variables are only significant when another predictor is held constant.
- Standard errors of the individual coefficient estimates may be biased downward, resulting in confidence intervals that are too narrow.

- Coefficient estimates may be biased away from zero if they are chosen based solely on their statistical significance.

To address some of these concerns, the ordering used to test the variables was explored. Regardless of the ordering, the model was repeatedly narrowed down to the same set of variables and final model specification. An additional potential drawback of stepwise regression analysis is the inability to identify individual variable effects in the presence of high multicollinearity (strong linear relationship between independent variables). This does not impact predictions on the dependent variable (relining cost) but can impact expected signs and magnitudes of individual coefficients, such as those estimated for pipe physical features and application type. In general, variables that are highly correlated are not included together in the final model (e.g., area relined and pipe length), meaning there is not a high degree of multicollinearity in the final specification.

A.4 Quantity Regressions

The first set of regressions (Models Q1–Q3) focus on the area relined (quantity) to determine the best functional form for the hedonic cost equation. Quantity is a priori expected to be a key predictor of ATC, which generally falls as quantity increases, implying economies of scale. The following regression specifications are tested to examine the relationship between quantity and ATC for relining a large diameter pipe (*i*).

$$ATC_i = \beta_0 + \beta_1 Q_i + e_i \tag{Q1}$$

$$ATC_i = \beta_0 + \beta_1 Q_i + \beta_2 {Q_i}^2 + e_i \tag{Q2}$$

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + e_i \tag{Q3}$$

The residual (*e*) for each model, sometimes called the model error, reflects the difference between the observed values and predicted values, and the objective of OLS regression is to find the fitted line that minimizes the model residuals. Model Q1 is a simple univariate level-level regression between ATC and area relined where β_0 is the estimated intercept and the coefficient on quantity (β_1) reflects the slope of the fitted line. A negative coefficient estimate on quantity would indicate that ATC falls as quantity increases, implying economies of scale. The intercept is not reported since there is no setting where quantity would be zero, meaning it is not appropriate to interpret the intercept. Model Q2 includes a quadratic term for area relined to test for a non-linear relationship in quantity. Model Q3 tests a log-log specification, which focuses on the geometric mean of ATC and quantity instead of the arithmetic mean. The results from these models are reported in Table A-1, followed by a discussion on each specification.

Table A-1. Regression Results for quantity relined

Independent Variable	Model Q1	Model Q2	Model Q3
Area Relined (1,000 sqft)	-0.289** (0.125)	-1.222*** (0.318)	
Area Relined (1,000 sqft), Squared		0.000002*** (0.0000006)	
ln(Area Relined)			-0.312*** (0.021)
Dependent Variable			
Level	X	X	
Natural Log			X
R-squared	0.0762	0.1750	0.7044
RMSE	59.250	56.389	0.269

Robust standard errors in parenthesis. Statistical Significance: ***1% Level, **5% Level, *10% Level.

Model Q1 is a simple univariate regression between ATC and area relined, both measured in level form. The coefficient estimate on quantity is statistically significant at the 5 percent level and indicates that every 1,000 sqft increase in area relined corresponds with a $0.29 decrease in ATC. The negative coefficient implies economies of scale, or that ATC falls as the quantity relined increases. The model R-squared is only 0.0762, which means that less than 8 percent of the variation in ATC is explained by this model. Another way to examine the error of the model is to look at the Root Mean Squared Error (RMSE). This can be thought of as the standard deviation of the unexplained variance and is in the same units as the dependent variable. This is a measure of how far off the actual values are from the predicted values, meaning a lower RMSE is preferable. For Model Q1, the RMSE is 59.25 meaning the model is on average off by about $59.25 per sqft.

A Ramsey Regression Equation Specification Error Test (RESET) test examines whether a non-linear specification would better explain the dependent variable. A Ramsey RESET test for Model Q1 suggests that a non-linear specification for quantity would provide a better fit. Model Q2 includes a quadratic term for area relined, which allows for a second-degree polynomial relationship between quantity and ATC. The model indicates that ATC falls as area relined increases, but at a decreasing rate (indicated by a positive sign on the quadratic term). This again indicates economies of scale, but the effect diminishes as quantity increases. The coefficient estimates for Model Q2 are found to be statistically significant at the 1 percent level, R-squared increases to 0.1750, and RMSE falls to $56.39, suggesting that this model provides a slightly better prediction than Model Q1. While Model Q2 outperforms Model Q1, a Ramsey RESET test still suggests that the model is misspecified. Recall that the distributions of area relined, and ATC are both skewed in level form, but closer to a normal distribution on a logarithmic scale. This means that the estimates in Models Q1 and Q2 might be biased by outliers and that a logarithmic transformation might improve the model specification.

Model Q3 tests a log-log specification, meaning the model examines how the natural log of ATC is influenced by the natural log of area relined. In this specification, the coefficient identifies the percent change in ATC associated with a one percent change in quantity. This specification is less likely to be biased by outliers since it focuses on the geometric mean and the distribution of both the dependent and independent variable are less skewed on a logarithmic scale. Looking at Model Q3 the coefficient on quantity is statistically significant at the 1 percent level and indicates that a 1 percent increase in area relined corresponds with about a 0.31 percent decrease in ATC. The R-squared for Model Q3 jumps to 0.7044, meaning over 70 percent of the sample variation in ATC is explained by the model and quantity alone. With TC modeled as the dependent variable in a log-log specification, R-squared is even higher at 0.9203, meaning 92 percent of the sample variation in TC is explained by quantity alone. RMSE in both models is 0.269, suggesting the model predictions are on average off by 26.9 percent. A Ramsey RESET test for Model Q3 shows that the model is now properly specified in quantity. This is consistent with Figure 4-6 which previously showed a log-linear relationship between ATC and quantity. Model Q3 is therefore deemed preferable to Models Q1 and Q2.

Although not reported here, both a level-log and log-level specification were also tested. These specifications did not pass the Ramsey RESET test or provide as strong a fit (R-squared) as Model Q3, so the results are not reported. A quadratic term for the natural log of quantity was also tested, but this was deemed unnecessary and did not improve the model fit. Models Q1–Q3 all show a statistically significant relationship between quantity relined and ATC and indicate economies of scale, but Model Q3 is deemed the preferred specification for estimating this relationship. The high R-squared on Model Q3 indicates that quantity relined is a key predictor of ATC and alone explains a large part of the variation. Nonetheless, there still remains some unexplained variation in ATC, and several other variables worth testing to see if they might improve the predictive power of the model. Model Q3 is therefore carried forward to test additional variables of interest.

It is worth mentioning that two other variables that are closely related to the quantity relined were also tested. The first is *area relined as a percentage of total area* and the next is a binary variable for *spot repair versus full reline*. As one might expect, both of these variables are highly correlated with area relined, making it unreasonable to include more than one of these variables together in the model. It is also not obvious how one might interpret the coefficients if including more than one of these quantity measures together. Given this, each variable was tested individually, and area relined proved to offer the best fit and greatest predictive power. This is not too surprising since *spot repair versus full reline* is only a binary variable, and while *area relined as a percentage of total area* is continuous, it is in part influenced by the size of each pipe. This means that a continuous variable for area relined is the ideal variable for capturing quantity information, as done in Model Q3.

A.5 Location, Time, and Ownership Regressions

The cost of relining is potentially influenced by geographic location, time, and even ownership. Locational differences are examined for Reclamation regions as well as states. Reclamation regions provided a stronger model fit using fewer variables, so this is shown below and included in the model. Time is also tested as a variable, which is defined by the year the contract was awarded. The coefficient estimate therefore reflects whether there is any average change in cost year-over-year. This variable accounts for possible exogenous macroeconomic trends not explicitly captured by variables in the model that might influence cost across time for all relining jobs. Finally, a binary variable for Reclamation ownership is examined, identifying any differences in the average cost for Reclamation relative to other entities included in the sample. The following models are tested:

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Time_i + e_i \qquad \text{(TOL1)}$$

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Reclamation_i + e_i \qquad \text{(TOL2)}$$

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_R Region_i + e_i \qquad \text{(TOL3)}$$

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_R Region_i + e_i \qquad \text{(TOL4)}$$

Model TOL1 includes a continuous variable for time to examine possible trends across the sample period. The sample spans 1999-2020 so time is redefined as $t=1,\ldots,T$ to simplify the variable and prevent a negative intercept in the model. Model TOL2 includes a binary variable for Reclamation ownership to test for any differences in cost. Model TOL3 models differences across the five Reclamation regions with a series of binary variables, excluding one as the reference group, where β_R is a vector of coefficients for the regional indicators. This reflects variables for the Upper Colorado Region, Lower Colorado Region, Columbia Pacific-Northwest Region, California Great Basin Region, and the Missouri Basin and Arkansas-Rio Grande-Texas Gulf Region. The Lower Colorado Region is treated as the reference group. Model TOL4 controls for both Reclamation ownership and Reclamation region. Table A-2 shows the results for these models.

Table A-2. Regressions for ownership and location

Independent Variable	**Model TOL1**	**Model TOL2**	**Model TOL3**	**Model OL4**
ln(Area Relined)	-0.312*** (0.021)	-0.289*** (0.027)	-0.323*** (0.035)	-0.279*** (0.030)
Time	-0.014 (0.010)			
Reclamation Ownership		0.229* (0.142)		0.525*** (0.152)
Region				
California Great Basin			-0.087 (0.217)	-0.153 (0.218)
Columbia Pacific-Northwest			-0.223** (0.114)	-0.448*** (0.151)
Missouri Basin/Arkansas-Rio Grande-Texas Gulf			-0.416** (0.171)	-0.528*** (0.163)
Upper Colorado			-0.197* (0.122)	-0.407*** (0.154)
R-squared	0.7233	0.7243	0.7628	0.8331
RMSE	0.262	0.261	0.248	0.209

Robust standard errors in parenthesis. Statistical Significance: ***1% Level, **5% Level, *10% Level.

Model TOL1 tests for a possible time trend across the sample period. The coefficient estimate for quantity is unaffected while the coefficient on the time variable is negative but not statistically significant. The lack of statistical significance could be due to the fact that the sample is adjusted to

2020$ values using Reclamation's CCT, meaning values are already adjusted for changes in price levels. The coefficient estimate therefore suggests that there is no significant time trend in real values across the sample period. The model R-squared and RMSE also do not change much. Time is therefore excluded from the model as a variable and the price level adjustment is assumed to account for aggregate trends across time. This variable is tested again in later models that control for other factors, but the estimate remains insignificant.

Model TOL2 includes a binary variable for Reclamation ownership and the estimate indicates that the agency on average pays more than other entities. The coefficient on the binary variable for Reclamation ownership is statistically significant at the 10 percent level and suggests that Reclamation pays about 23 percent more for relining than other entities. This could be due to contractors charging a higher markup, federal requirements for minimum labor rates, or due to unknown differences between Reclamation and other entities not currently captured in the model. Regardless of the reason, Model TOL2 suggests that it is important for the model to account for Reclamation ownership when predicting cost. Also note that the magnitude on the coefficient estimate on quantity decreases a bit when accounting for ownership. This suggests that the estimate may have previously been biased upward by not accounting for Reclamation ownership.

Model TOL3 tests a series of binary variables for Reclamation regions. The estimate on quantity is a bit higher than in Model Q3 and R-squared increases to 0.7628 while RMSE falls to 0.248, suggesting that it may be important to control for locational differences. The coefficient estimates for the regional indicators are negative and statistically significant, other than for the California Great Basin Region. This suggests that cost is highest in the Lower Colorado Region, which is the reference group, and then varies across other regions. In later models, the coefficient estimates for the regional indicators are all statistically significant. Reclamation region is also a useful variable for making predictions in line with the study objective to predict future Reclamation spending across regions. Regional indicators are therefore kept in the model.

Model TOL4 includes a binary variable for Reclamation ownership and binary variables for Reclamation regions. In this specification, R-squared increases to 0.8331, RMSE falls to 0.209, and the estimates on ownership and region improve. The coefficient estimate for Reclamation ownership becomes highly statistically significant and now suggests that Reclamation pays about 52.5 percent more than other entities. The coefficients on the regional indicators also increase in magnitude and statistical significance, other than the estimate for the California Great Basin Region, which increases in magnitude but is still not statistically significant with the Lower Colorado Region as the reference group. The coefficient on quantity is again lower than in Model Q3, suggesting that location and ownership help reduce some previous omitted variable bias. Model TOL4 is carried forward to test additional variables of interest.

A.6 Physical Features Regressions

The next set of regressions focus on pipe physical features (slope, diameter, and length) and pick up from Model TOL4. Expectations are that a greater diameter and greater slope might increase ATC due to increasing the difficulty and time it takes to conduct relining. Pipe length is also tested, with the expectation that a greater length might increase cost due to reduced access. That said, pipe length is highly correlated with the area relined, so the results for pipe length are not statistically significant when area relined is kept in the model and the estimate picks up economies of scale when area relined is excluded. The results from testing pipe length are therefore not reported and the focus of this section is on pipe diameter and slope.

The UW, LW, and AW measures of diameter and slope produce very similar estimates, so attention is placed on the AW measures. The AW measures are deemed the most appropriate since the area relined is a key variable in the model and this proportions the slope and diameter of each pipe section by the area relined in that particular section. The AW measures also prove to generate estimates with slightly higher statistical significance than the LW measures, though the magnitude of the estimates is very similar. Models P1-P3 are used to examine whether AW pipe diameter and slope might affect ATC.

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_R Region_i + e_i \quad \text{(P1)}$$

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Slope_i + \beta_R Region_i + e_i \quad \text{(P2)}$$

$$\begin{aligned}\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_4 AW\ Slope_i \\ + \beta_R Region_i + e_i\end{aligned} \quad \text{(P3)}$$

Model P1 tests whether pipe AW diameter (ft) affects ATC. Model P2 tests whether pipe AW slope (degrees) affects ATC. Model P3 includes both AW diameter and AW slope in the model. Pipe diameter and slope were also tested using a log transformation, quadratic terms, and an interaction variable, but these proved to be unnecessary and did not improve the model fit. Table A-3 shows the results for Models P1–P3.

Model P1 includes AW diameter in the model. The coefficient estimate for AW diameter is not statistically significant and adding this variable has little impact on the overall model fit and other coefficient estimates in the model. Testing a log transformation and quadratic term for AW diameter did not improve the estimate or model fit, even though a natural log transformation makes the distribution closer to normal, as previously shown. In later regressions, once separating the effect of diameter for robotic versus manual application, the estimate for diameter becomes statistically significant. AW diameter is therefore kept in the model.

Model P2 tests AW slope in the model. The coefficient estimate is statistically significant at the 1 percent level and indicates that every 1 degree increase in slope increases ATC by about 1 percent. R-squared increases to 0.8628 and RMSE falls to 0.191, suggesting that pipe slope helps explain some of the variation in ATC. Testing a log transformation and quadratic term for AW slope did not improve the estimate or model fit, nor did an interaction variable between pipe diameter and slope. The estimates for quantity and Reclamation ownership slightly change in magnitude, suggesting that these may have been slightly biased without controlling for pipe slope. Pipe slope is therefore kept in the model, which in later models is found to have a different effect on cost depending on whether robotic or manual application is used. Model P3 includes both AW diameter and AW slope. The model is similar to Model P2 and the estimate for diameter is not statistically significant until later model specifications. Model P3 is carried forward to test additional variables of interest.

Table A-3. Regressions for physical features

Independent Variable	Model P1	Model P2	Model P3
ln(Area Relined)	-0.280*** (0.032)	-0.297*** (0.031)	-0.298*** (0.031)
Reclamation Ownership	0.557*** (0.144)	0.473*** (0.129)	0.502*** (0.130)
AW Diameter	-0.004 (0.004)		-0.004 (0.004)
AW Slope		0.010** (0.004)	0.010** (0.004)
Region			
California Great Basin	-0.215 (0.204)	-0.151 (0.172)	-0.207 (0.172)
Columbia Pacific-Northwest	-0.470*** (0.142)	-0.608*** (0.158)	-0.626*** (0.159)
Missouri Basin/Arkansas-Rio Grande-Texas Gulf	-0.589*** (0.147)	-0.512*** (0.142)	-0.567*** (0.142)
Upper Colorado	-0.473*** (0.131)	-0.425*** (0.126)	-0.484*** (0.124)
R-squared	0.8358	0.8628	0.8650
RMSE	0.209	0.191	0.191

Robust standard errors in parenthesis. Statistical Significance: ***1% Level, **5% Level, *10% Level.

A.7 Lining Type Regressions

The next set of regressions pick up from Model P3 and focus on lining type, testing both the existing lining type and new lining type. Since relining jobs include removing existing linings and preparing the surface, the existing lining may influence the cost of relining. Meanwhile, the new lining type used might also have important implications on overall cost due to differences in the cost of materials. Given that there are numerous lining types, each type is grouped under a broad category as being either coal tar enamel, epoxy, polyurethane, vinyl, or cement mortar. There is however a range of lining types within most of these categories, which is more than the model can accommodate. A binary variable for polymer linings is also examined, which excludes coal tar enamel and cement mortar. This is only applicable to the existing lining type, as polymer linings are the only type in the sample used for the new lining.

Recall from the descriptive statistics that about 88 percent of the sample observations have coal tar enamel for the existing lining type and about 90 percent use epoxy-based linings for the new type. Given that there are so few observations of other lining types in the sample, the a priori expectation is that the model may not be able to distinguish effects on cost between lining types. Furthermore, surface preparation is often similar regardless of the existing lining, and the cost of the new lining material is generally a small portion of the overall cost of relining. Nonetheless, there may be some particular lining types that stand out as affecting cost, so this is explored. To examine the potential influence of lining types, a series of binary variables are tested in Models L1–L3.

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_4 AW\ Slope_i + \beta_R Region_i + \beta_E Existing\ Lining_i + e_i \quad \text{(L1)}$$

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_4 AW\ Slope_i + \beta_R Region_i + \beta_N New\ Lining_i + e_i \quad \text{(L2)}$$

$$\ln ATC_i = \beta_0 + \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_4 AW\ Slope_i + \beta_R Region_i + \beta_E Existing\ Lining_i + \beta_N New\ Lining_i + e_i \quad \text{(L3)}$$

Model L1 focuses on the existing lining type and includes a binary variable for cement mortar, epoxy, polyurethane, and vinyl, with coal tar enamel as the reference group, and β_E reflects a vector of coefficients for the existing lining indicators. A binary variable for polymer linings was also examined but not found to be statistically significant. Model L2 examines the new lining type and includes a binary variable for polyurethane and vinyl, with epoxy as the reference group, and β_N reflects a vector of coefficients for the new lining indicators. Model L3 includes binary indicators for both the existing and new lining types. The reference groups were chosen since they encompass the majority of observations in the sample. The results for Models L1–L3 are shown in Table A-4.

Model L1 examines the existing lining type, which is measured using binary variables for each type in the sample, with coal tar enamel as the reference group. The model suggests that the existing lining type is not a strong predictor of cost, though the estimate for cement mortar is statistically significant at the 5 percent level and suggests that cement mortar is cheaper to remove and prepare than coal tar enamel. However, there are only 3 observations of cement mortar in the sample, and this specification pushes the limits of the sample and degrees of freedom in the model, forcing the binary indicator for vinyl to be omitted due to insufficient observations. This specification adds several variables to the model with minimal improvement in the model predictions. As shown in Model P3, once controlling for the new lining type, the statistical significance for the coefficient on cement mortar goes away. With the limited variation in the existing lining type and lack of statistical significance, the project team did not feel this was a reasonable variable to use to make predictions.

Model L2 examines the new lining type used, which is again measured using binary variables for each type in the sample. The coefficient estimate for new lining type polyurethane is statistically significant at the 1 percent level and indicates that polyurethane is cheaper than epoxy. However, there are only 6 observations in the sample with polyurethane as the new lining type, again raising concerns about the reliability of using the coefficient estimate in the final model. As with the existing lining type, the project team did not feel it was reasonable to use the new lining type to make predictions, which is due to the limited sample size and concern of making generalizations.

Model L3 includes binary variables for the existing lining type and new lining type. As shown this adversely affects the estimates for other variables in the model and only the estimate for new lining polyurethane is statistically significant. When running the model again with only the binary indicator for new lining polyurethane, the model is almost identical to Model L3, suggesting that all of the remaining lining variables do not improve the model fit. Although the case could potentially be made to keep a binary variable for new lining polyurethane in the model given the high statistical significance, the project team was concerned that this estimate could be a "false positive" (known as a Type 1 error). While there may in fact exist a cost difference for the different lining types, the project team ultimately decided that the limited sample variation prevents using lining types for making reliable predictions. Variables for the existing and new lining type are therefore excluded from the model and Model P3 is carried forward to test robotic versus manual application.

Table A-4. Regressions for lining type

Independent Variable	Model L1	Model L2	Model L3
ln(Area Relined)	-0.286*** (0.037)	-0.259*** (0.029)	-0.234*** (0.039)
Reclamation Ownership	0.405*** (0.087)	0.477*** (0.104)	0.527*** (0.109)
AW Diameter	-0.004 (0.004)	-0.004 (0.004)	-0.004 (0.003)
AW Slope	0.009* (0.005)	0.008* (0.005)	0.008 (0.006)
Region			
California Great Basin	-0.198 (0.168)	-0.095 (0.168)	-0.058 (0.164)
Columbia Pacific-Northwest	-0.581*** (0.184)	-0.622*** (0.165)	-0.591*** (0.197)
Missouri Basin/Arkansas-Rio Grande-Texas Gulf	-0.513*** (0.106)	-0.371*** (0.127)	-0.333*** (0.134)
Upper Colorado	-0.442*** (0.124)	-0.488*** (0.117)	-0.449*** (0.129)
Existing Lining Type			
Cement Mortar	-0.332** (0.153)		0.168 (0.221)
Epoxy	0.131 (0.098)		0.165 (0.108)
Polyurethane	-0.028 (0.391)		0.208 (0.247)
Vinyl	Omitted		Omitted
New Lining Type			
Polyurethane		-0.452*** (0.125)	-0.582*** (0.172)
Vinyl		-0.126 (0.120)	-0.159 (0.136)
R-squared	0.8804	0.8981	0.9037
RMSE	0.184	0.169	0.168

Robust standard errors in parenthesis. Statistical Significance: ***1% Level, **5% Level, *10% Level.

A.8 Application Technology Regressions

To test the influence of robotic versus manual application, a binary variable is defined to indicate if robotic application was used. This variable is tested alone, and as an interaction variable with several variables already in the model, with particular interest on interactions with area relined, pipe diameter, and pipe slope. The rationale for these interaction variables is to test whether the effects for area relined and pipe physical features influence cost differently depending on whether robotic or manual application is used. While several model specifications were tested, Model A1–A4 are reported and discussed below. Each of these build from Model P3.

$$\begin{aligned}\ln ATC_i = \beta_0 &+ \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_4 AW\ Slope_i \\ &+ \beta_5 Robotic_i + \beta_R Region_i + e_i\end{aligned} \tag{A1}$$

$$\begin{aligned}\ln ATC_i = \beta_0 &+ \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_4 AW\ Slope_i \\ &+ \beta_5 Robotic_i + \beta_6 (Robotic_i * AW\ Diameter_i) + \beta_R Region_i + e_i\end{aligned} \tag{A2}$$

$$\begin{aligned}\ln ATC_i = \beta_0 &+ \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_4 AW\ Slope_i \\ &+ \beta_5 Robotic_i + \beta_6 (Robotic_i * AW\ Diameter_i) + \beta_7 (Robotic_i \\ &* AW\ Slope_i) + \beta_R Region_i + e_i\end{aligned} \tag{A3}$$

$$\begin{aligned}\ln ATC_i = \beta_0 &+ \beta_1 \ln Q_i + \beta_2 Reclamation_i + \beta_3 AW\ Diameter_i + \beta_4 AW\ Slope_i \\ &+ \beta_5 (Robotic_i * AW\ Diameter_i) + \beta_6 (Robotic_i * AW\ Slope_i) \\ &+ \beta_R Region_i + e_i\end{aligned} \tag{A4}$$

Model A1 includes a binary variable for robotic application to test if the average cost of robotic application differs from manual application. Model A2 adds an interaction variable for robotic application and pipe diameter to test whether diameter affects cost differently for robotic versus manual application. A natural log transformation and quadratic term for pipe diameter was also retested and as before this did not improve the model fit. Model A3 adds an interaction variable for robotic application and pipe slope to test whether slope affects cost differently for robotic versus manual application. A natural log transformation and quadratic term for pipe slope was also retested, but this did not improve the model. Model A4 drops the binary variable for robotic application, meaning differences between the cost of robotic and manual application are only modeled through the effect of pipe diameter and slope on cost. This has no impact on the model, suggesting that these are the only avenues in which robotic and manual application differ in cost. Table A-5 shows the results for these model specifications.

Model A1 includes a binary variable for robotic application to test if the average cost of robotic application differs from manual application. The coefficient estimate is statistically significant at the 1 percent level and suggests that the cost for robotic application is on average about 28 percent more than manual application. After adding a binary variable for robotic application the coefficient estimate for quantity becomes notably larger in magnitude, and the regional indicator for the California Great Basin becomes statistically significant, suggesting that controlling for application type improves the estimates. While this model suggests that robotic application is on average more costly than manual application, the next step is to test whether some of the variables already in the model, namely the quantity relined, pipe slope, and pipe diameter, might affect cost differently for robotic application versus manual application.

Table A-5. Regressions for application type

Independent Variable	Model A1	Model A2	Model A3	Model A4
ln(Area Relined)	-0.375*** (0.031)	-0.368*** (0.026)	-0.367*** (0.026)	-0.369*** (0.025)
Reclamation Ownership	0.486*** (0.123)	0.503*** (0.121)	0.553*** (0.123)	0.553*** (0.061)
AW Diameter	-0.001 (0.009)	-0.004* (0.026)	-0.010*** (0.004)	-0.010*** (0.004)
AW Slope	0.009** (0.004)	0.013*** (0.005)	0.022*** (0.007)	0.022*** (0.007)
Robotic Application	0.280*** (0.052)	-0.163 (0.207)	-0.034 (0.158)	
*Robotic Application * AW Diameter*		0.029** (0.013)	0.032*** (0.012)	0.030*** (0.008)
*Robotic Application * AW Slope*			-0.011* (0.006)	-0.011** (0.005)
<u>Region</u>				
California Great Basin	-0.423** (0.165)	-0.426*** (0.153)	-0.417*** (0.147)	-0.420** (0.149)
Columbia Pacific-Northwest	-0.749*** (0.158)	-0.845*** (0.164)	-0.918*** (0.143)	-0.915*** (0.140)
Missouri Basin/Arkansas-Rio Grande-Texas Gulf	-0.554*** (0.136)	-0.557*** (0.134)	-0.623*** (0.136)	-0.624*** (0.133)
Upper Colorado	-0.436*** (0.114)	-0.501*** (0.117)	-0.574*** (0.119)	-0.571*** (0.118)
R-squared	0.8989	0.9101	0.9200	0.9199
RMSE	0.167	0.159	0.151	0.149

Robust standard errors in parenthesis. Statistical Significance: ***1% Level, **5% Level, *10% Level.

An interaction variable between robotic application and area relined was tested first, which would identify differences in economies of scale for robotic versus manual application. The estimate for this interaction variable was not statistically significant and did not improve the model fit, so the results are not reported or discussed. That said, interaction variables that allow the effect of pipe diameter and slope to differ for robotic versus manual application proved to be important.

Model A2 includes a binary variable for robotic application as well as an interaction variable between robotic application and AW diameter to test whether diameter affects cost differently for robotic versus manual application. The coefficient estimate on the binary variable for robotic application flips in sign to a negative estimate and is no longer statistically significant. Meanwhile, the interaction variable between robotic application and diameter is statistically significant at the 1 percent level and indicates that every one-foot increase in diameter increases the cost of using robotic application by about 2.9 percent more than for manual application. This suggests that the previous positive coefficient estimate for the robotic application binary variable from Model A1 was likely being driven by cost being higher with a larger diameter. Nonetheless, the binary variable for robotic application is kept in the model for now since the coefficient magnitude is still relatively large.

Model A2 indicates that robotic application may or may not be cheaper than manual application, depending on pipe diameter. For manual application, the model actually indicates that cost decreases about 1 percent for each one-foot increase in diameter, as signified by the coefficient estimate on diameter alone, which captures the effect of diameter for manual application. This is the first time the coefficient for pipe diameter is statistically significant, suggesting that it is important to distinguish between robotic and manual application. The negative coefficient estimate for manual application was somewhat unexpected at first but makes some intuitive sense. Manual application requires getting workers, equipment, and materials into the pipe, which is difficult in confined spaces and small diameter pipes but gets easier as diameter increases. For robotic application, only the robot needs to fit into the pipe, and robotics have historically been used to reline smaller pipes that workers are not able to fit inside. Meanwhile, it can be difficult to use robotic application on very large diameter pipes since the robot typically moves along the pipe floor, making it difficult to reach the entire pipe circumference as diameter increases. This likely explains the large positive estimate for the effect of diameter on the cost for robotic application. Overall, robotic application appears to be cheaper for small diameter pipes, while manual application is cheaper for large diameter pipes.

The next model tests whether the effect of slope on cost differs for robotics versus manual application. Model A3 includes an interaction variable for robotic application and pipe slope. The results indicate that increasing slope by one degree increases the cost of manual application by 2.2 percent (1 percent statistical significance), but only increases cost by 1 percent for robotic application (10 percent statistical significance). The effect for robotic application is indicated by the negative coefficient estimate on the interaction variable for robotic application and slope that offsets roughly half of the effect estimated for manual application. The result for slope is not too surprising given that as slope increases manual application requires scaffolding and safety equipment and robotic application requires special calibration, meaning both are generally more difficult on a steeper slope. Slope therefore appears to affect the cost of both robotic and manual application, though the effect appears to be about twice as large for manual application.

Model A3 indicates that pipe diameter and slope both affect cost differently depending on whether robotic or manual application is used. In general, the model shows that robotic application is cheaper for small steep pipes, while manual application is cheaper for large flat pipes. The marginal effects predicted by the model are plotted later on to show how diameter and slope affect cost differently for manual versus robotic application. In Model A3 the coefficient for the binary variable for robotic application is not statistically significant and is also relatively small in magnitude. This suggests that differences between the cost of robotic and manual application primarily manifest through differences in pipe diameter and slope. As shown by Model A4, dropping the binary variable for robotic application does not affect R-squared and RMSE actually decreases a bit. This model explains about 92 percent of the sample variation in ATC with an average prediction error of about 15 percent, making it a candidate for the final model specification.

At this point, there are no more variables of interest or model specifications to test, so the robustness of Model A4 is examined to determine if it is suitable as the final model. Keep in mind that various interaction variables and non-linear variable specifications were tested throughout the process of adding variables to arrive at Model A4. This model proved to provide the highest model fit using the fewest number of statistically significant variables. As discussed more in the next section, several variables are retested in Model A4 to see if they improve the model fit. This is followed by a robustness check on the model and a detailed discussion of the model predictions.

A.9 Final Regression Model

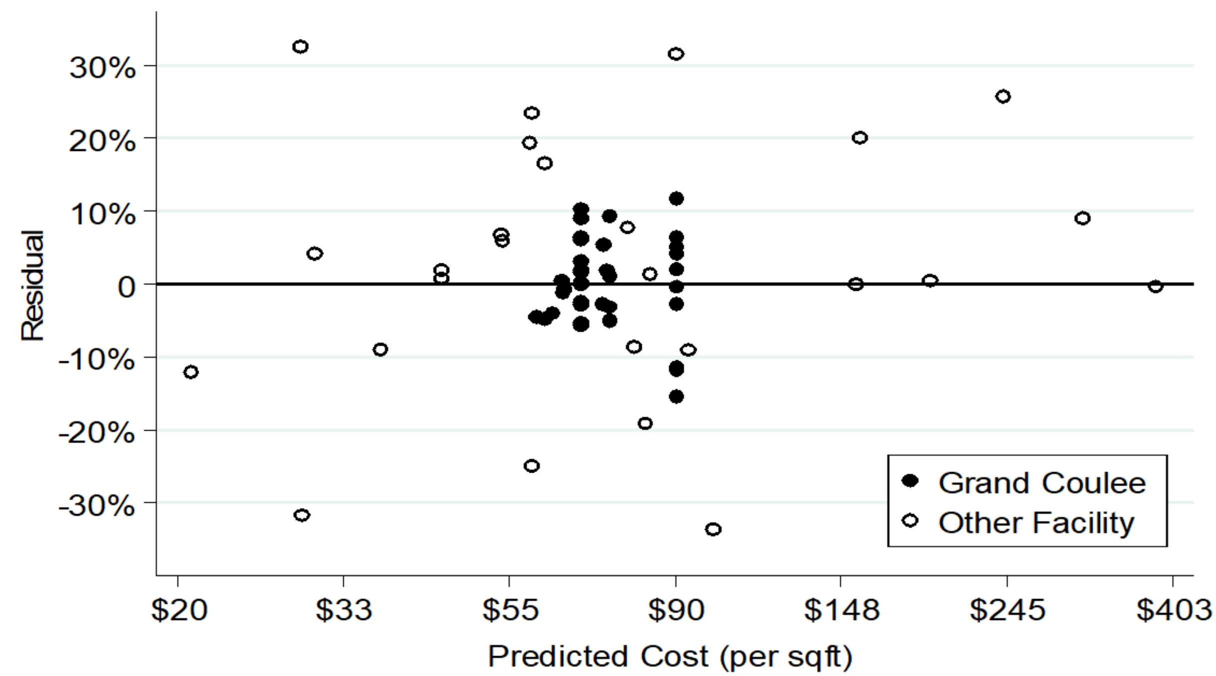
While the stepwise regression process that is shown to arrive at Model A4 was presented in a fairly linear manner, the actual process was more iterative and non-linear with several variables and model specifications tested along the way. The ordering used to test variables can sometimes affect the stepwise process, so this was also explored, and the models reported were tested in various orderings. Regardless of the ordering, the model was repeatedly narrowed down to the specification shown for Model A4. Also keep in mind that only those models found to be important and worthy of discussion were reported. Before considering Model A4 the final model specification, it is important to note that variables previously dropped from the model were retested to see if they improve the model fit and are statistically significant in this particular model specification. This process did not identify any other variables that should be added to Model A4.

Additional variables were also tested in Model A4, specifically those that data were collected for, but where there was no a priori expectations as predictors of cost. This includes a binary variable for whether the contract included non-relining work, a binary variable for whether the contract included relining a single pipe or multiple pipes, a continuous variable for the number of pipes relined on a single contract, and a continuous variable for the number of unique sections of a pipe (meaning diameter and/or slope changes). Some of these variables were found to be statistically significant on their own, but not once including the other variables found in Model A4. Model A4 therefore provides the strongest model fit using the fewest number of variables, meaning this is used for the final model specification. The robustness of this model is examined in the next section, followed by a section that shows the model predictions.

A.10 Final Model Robustness

Before adopting Model A4 as the final model specification, several robustness checks were performed. The first robustness check was to examine the need to adjust for heteroscedasticity, which is a non-constant variance in the model residuals (difference between actual values and predicted values) which can bias the estimates. All models that have been reported include the robust standard errors, which reflects an adjustment to standard errors to account for heteroscedasticity. That said, it is not clear whether this is necessary for the final model specification or not. Heteroscedasticity is common in cross-sectional regression analysis and adjusting for heteroscedasticity does not affect the magnitude of a coefficient estimate, only the statistical significance of that estimate. There is no downside to adjusting for potential heteroscedasticity, so best practice is to generally report robust standard errors, as done for all models up until now.

The presence of heteroscedasticity is evaluated by first visualizing the model residuals and then by conducting a Breusch-Pagan test and White test for heteroscedasticity. These tests examine whether the model residuals are distributed with equal variance (homoscedasticity). To use the model for making predictions, it is important that the model residuals are distributed randomly with no systematic patterns that might bias the estimates. Figure A-1 plots the residuals for Model A4 against the predicted ATC, which should be centered around zero and exhibit no obvious pattern across the predicted ATC if the residuals are homoscedastic. The predicted values in Figure A-1 are shown on a natural logarithmic scale but translated back into dollars per sqft for easier interpretation. The residuals are reported as a percentage since the model errors are fitted to natural-logged data and cannot be directly converted to dollars. A positive residual indicates that the actual value is above the predicted value and vice versa. The residuals show that the model predictions on average have a 15 percent error, which corresponds with the model RMSE of 14.9 percent.



Notes: Cost per sqft (ATC) is shown on a natural logarithmic scale.

Figure A-1. Regression model A4 residuals

Figure A-1 does not show any obvious pattern across the predicted values, however, there does appear to be a bit of a cluster of residuals towards the center of the distribution. After closer examination, it appears that many of these belong to a particular Reclamation facility, Grand Coulee. These particular observations are highlighted in Figure A-1. Grand Coulee is a unique facility, not only because of the extreme physical features (very large pipe diameter and slope), but also because this facility makes up a large number of the observations in the sample. This arises since Grand Coulee has both a powerplant and pumping plant, both with numerous large diameter pipes, and multiple contracts were identified for relining work at this facility.

The inclusion of the large number of Grand Coulee observations prompted discussions early on about important robustness checks that might be needed to ensure that these observations are not driving the model estimates. The most obvious robustness check is to run the final model with the full sample and then again without the Grand Coulee observations and compare the model estimates for any major differences. The need for this robustness check is further supported by the residuals in Figure A-1 which suggest that these observations may be generating heteroscedasticity.

Table A-6 shows Model A4 run with the full sample and excluding the Grand Coulee observations. The unadjusted standard errors (SEs) are reported in the first set of parenthesis and the robust SEs are reported in the second set of parenthesis. Since the coefficient estimate is the same, and only the SEs change, statistical significance is shown on the SE estimates. For the unadjusted model, the Breusch-Pagan and White test statistics for heteroscedasticity are reported at the bottom of the table. If the probability value of the chi-square statistic (prob > chi2) is below 0.1 then it is an indication of heteroscedasticity at the 10 percent significance level. The table also reports the adjusted R-squared values for the models with unadjusted SEs, which makes an adjustment to R-squared based on the number of variables in the model.

The results of the Breusch-Pagan and White tests indicate the presence of heteroscedasticity when the Grand Coulee observations are included in the sample, but this goes away when these observations are excluded. This means that the heteroscedastic-robust standard errors are needed when modeling the full sample, or it might be necessary to at least cluster the SEs by facility (clustering is discussed more below). The second set of parenthesis in the table show the robust standard errors which account for heteroscedasticity. Most of the model estimates with the full sample are statistically significant using both unadjusted SEs as well as robust SEs, but using robust SEs generally reduces the statistical significance of the estimates, as indicated by larger SEs.

Another important robustness check from Table A-6 is to compare the coefficient estimates and model fit with versus without the Grand Coulee observations. None of the coefficient estimates change in sign when the Grand Coulee observations are excluded. For some of the variables there is a slight change in magnitude and statistical significance of the coefficient estimate. This is not too surprising given that the Grand Coulee observations notably add to the sample variation for most of the variables in the model, which generally helps improve statistical significance. Looking at the model fit, excluding Grand Coulee appears to actually improve R-squared from 0.9199 to 0.9379, but the adjusted R-squared is nearly identical at 0.9070. Overall, the Grand Coulee observations do not appear to drive the main results of the model but do seem to generate heteroscedasticity and affect the statistical significance of the estimates, which can be corrected for with heteroscedastic-robust SEs. As such, all models shown for the stepwise regression analysis report the robust SEs.

Table A-6. Test for Heteroscedasticity

Independent Variable	**Model A4** (Full Sample)	**Model A4** (Excluding Grand Coulee)
ln(Area Relined)	**-0.369** (0.022)*** (0.029)***	**-0.360** (0.036)*** (0.032)***
Reclamation Ownership	**0.553** (0.078)*** (0.123)***	**0.608** (0.161)*** (0.189)***
AW Diameter	**-0.010** (0.004)*** (0.004)***	**-0.027** (0.014)* (0.013)**
AW Slope	**0.022** (0.004)*** (0.007)***	**0.028** (0.007)*** (0.008)***
*Robotic Application * AW Diameter*	**0.030** (0.005)*** (0.008)***	**0.022** (0.021)* (0.011)**
*Robotic Application * AW Slope*	**-0.011** (0.004)*** (0.006)**	**-0.016** (0.014) (0.009)*
<u>Region</u>		
California Great Basin	**-0.420** (0.146)*** (0.145)***	**-0.578** (0.270)** (0.225)**
Columbia Pacific-Northwest	**-0.915** (0.081)*** (0.140)***	Omitted
Missouri Basin/Arkansas-Rio Grande-Texas Gulf	**-0.624** (0.082)*** (0.133)***	**-0.854** (0.211)*** (0.197)***
Upper Colorado	**-0.571** (0.115)*** (0.118)***	**-0.836** (0.259)*** (0.213)***
R-squared	0.9199	0.9379
Adjusted R-squared	0.9070	0.9069
<u>Heteroscedasticity Test</u>		
Breusch-Pagan, Prob > Chi2	0.0901	0.4186
White, Prob > Chi2	0.0001	0.3585

Unadjusted standard errors are in the first set of parenthesis and heteroscedastic-robust standard errors are in the second set of parenthesis. Statistical Significance: ***1% Level, **5% Level, *10% Level.

In addition to testing for heteroscedasticity, it is also worthwhile to examine clustered SEs, especially under particular circumstances. Clustered SEs are applicable to settings where observations may be subdivided into smaller groups (i.e., clusters) and where the sampling is correlated within each group. Clustered SEs are often justified by possible correlation in modeling residuals within each cluster, or when the full population cannot be randomly sampled and so clusters are sampled. In either case, clustering the SEs is necessary in order to make generalizations that go beyond the sample observations. For this analysis the sample was collected with clustering around contracts and facilities, as well as potential clustering around location (Reclamation region) and time (contract year). Testing clustered SEs around each of these groupings is important if there are clusters in the population of interest that are not represented in the sample. Even with the model controlling for some of these factors, for example region, it may still be important to cluster SEs.

Table A-7 shows the clustered SEs around contract, facility, Reclamation region, and the contract year, respectively. Each of these are shown in parenthesis to the right of the coefficient estimates. Since this does not affect the coefficients, statistical significance is again shown on the SEs instead of the coefficient, as done in the previous table. As shown, those coefficient estimates previously found to be statistically significant remain significant across all forms of clustering. In some cases, clustering improves the statistical significance of the estimates beyond using the heteroscedastic-robust and unadjusted SEs.

Table A-7. Clustered standard errors for Model A4

Independent variable	Coefficient	Model A4 standard errors			
		Contract	Facility	Region	Contract year
ln(Area Relined)	-0.369	(0.021)***	(0.025)***	(0.028)***	(0.017)***
Reclamation Ownership	0.553	(0.118)***	(0.062)***	(0.028)***	(0.118)***
AW Diameter	-0.010	(0.004)**	(0.004)**	(0.005)*	(0.004)**
AW Slope	0.022	(0.008)***	(0.008)***	(0.004)***	(0.007)***
*Robotic Application * AW Diameter*	0.030	(0.008)***	(0.008)***	(0.003)***	(0.008)***
*Robotic Application * AW Slope*	-0.011	(0.006)*	(0.006)*	(0.001)***	(0.006)*
Region					
California Great Basin	-0.420	(0.123)***	(0.125)***	(0.117)**	(0.099)***
Columbia Pacific-Northwest	-0.915	(0.110)***	(0.088)***	(0.056)***	(0.119)***
Missouri Basin/Arkansas-Rio Grande-Texas Gulf	-0.624	(0.126)***	(0.081)***	(0.065)***	(0.151)***
Upper Colorado	-0.571	(0.093)***	(0.076)***	(0.081)***	(0.093)***

Statistical Significance: ***1% Level, **5% Level, *10% Level.

Table A-7 shows that the model estimates are robust to clustering the SEs around various groupings. Clustering the SEs around facility is deemed most appropriate given how the sample was collected. The sample is structured such that several observations are for pipes at the same facility, and most facilities in the sample have had multiple pipes relined. Clustering around facility also addresses the heteroscedasticity which was found when Grand Coulee is included in the sample. Given the robustness of Model A4, this is used as the final model specification and the estimates are based on clustered SEs around facility. The next section covers the final model in more detail and shows the predicted marginal effects when each variable in the model changes.

Appendix B. Relining Job Data Item Description Tables

Table B-1. Relining job data items evaluated and used in analysis

Variable	Definition	Expected Value	Importance
Contract Cost Year	Year that the contract was awarded.	Year in YYYY format.	Award year provides the basis for indexing all observations to a common price level for comparison.
Coating Repair Area	The total area that has been removed and relined.	A numerical value with units of square feet (sqft).	The repair area is proportional to the effort required and the associated costs for labor and materials, e.g., abrasive blast media and coatings.
Total Contract Cost	Summation of all costs in the contract.	Monetary value in USD, not adjusted for inflation.	This represents the total cost of the contract including coatings-related work as well as all other project work.
Coating Cost	Summation of coating costs in the contract.	Monetary value in USD, not adjusted for inflation.	This represents the coating cost within of the contract for water jetting or cleaning, abrasive blasting, coating application, and ventilation.
Robotic Application	Whether robotics was utilized to remove existing coating, perform surface preparation, or apply new coatings.	“Manned” indicating use of manned robotics, “Unmanned” indicating use of unmanned robotics, or “No Robotic” indicating no robotic devices were utilized.	Performing work with robotics can impact project completion time, efficiency, improve access to difficult to line areas and safety, potentially reduce incidence of improperly applied lining, among many other impacts. Manned robotics require one or more applicators in the area to control/move or operate the robot whereas unmanned robotics require less intervention from on-site personnel.
Existing Lining Type	The general category of coating system that was removed and replaced during the project.	A general category of coating system, e.g., coal tar enamel, vinyl, epoxy, polyurethane, and cement mortar lining.	Some linings require greater effort to remove or hazardous materials abatement.
New Lining Type	The general category of coating system that was newly applied during the project.	A general category of coating system, e.g., coal tar enamel, vinyl, epoxy, polyurethane, and cement mortar lining.	Some linings require greater effort, e.g., for surface preparation, environmental control, number of coats, or safety.
Location	Reclamation region that the relining occurs in. State is also examined.	Reclamation’s five regions: Upper Colorado Basin Region (UC), Lower Colorado Basin Region (LC), Columbia-Pacific Northwest Region (CPN), California-Great Basin Region (CGB), and Missouri Basin and Arkansas-Rio Grande-Texas Gulf Region (MBA)	The influence of location on cost is explored in case there are any locational differences found for historic observations.
Reclamation-Owned	Variable indicating if the pipe is owned by Reclamation or another entity.	Boolean, yes or no indication	Several factors could result in cost differences by pipe owner. Examples include owner differences in selection of project delivery method and wage rate constraints specific to Federal agencies.

Table B-2. Relining job data items evaluated and not used in analysis

Variable	Definition	Expected Value	Importance
Contract Type	Indicates whether the contract is for a spot repair (multiple small areas) or full relining (approximate total structure area).	Numerical value representing one of two options: Spot Repair = "0", Full Reline = "1."	Spot repairs may be completed in less time than a full relining and require less material, but mobilization and other costs do not scale in proportion to size of area relined. New pipe installs were not included because they do not include removal and disposal of existing coatings, etc.
Scaffolding Use	Whether or not scaffolding was utilized as part of the lining work.	Boolean, "Y" (yes) or "N" (no).	Construction, use, and tear down of scaffolding may represent an increase in project time and costs. Conversely, scaffolding may reduce costs and time by creating work platforms with multiple workers and increased worker maneuverability. Use of scaffolding may also introduce additional safety considerations and may be indicative of structure size.
Bid Type	Whether the project delivery method was negotiated, sealed, or an IDIQ.	Numerical value representing one of three options: Negotiated = "0", Sealed = "1", IDIQ = "2."	Relining jobs constituting the study sample were solicited, awarded, and paid-out through multiple different project delivery methods, which may have some effect on the overall contract cost, e.g., due to greater administrative effort by the contractor.
Mobilization and Preparatory Cost	Portion of the contract cost that goes toward contractor mobilization and preparatory work.	Monetary value in USD, not adjusted for inflation.	Mobilization and preparatory costs can vary based on many project conditions including site and structure access, whether there is work other than coatings work being done, contract type, type of existing and new coating, etc.
Proportion of total area relined	Repair area as a percent of total primary feature area.	0 to 100%.	Variable that might indicate the break-even point at which it is more cost-effective to perform a full reline rather than perform spot repairs.
Number of manholes, Do Manholes Open to Outdoors, Average Distance Between Manholes	These related column headings all involve manhole information. Number of manholes in the feature represents the total number of manholes, whereas Do Manholes Open to Outdoors provide an indication of manhole accessibility. Average distance between the manholes provides distances between manholes.	Number of Manholes- numeric value indicating total number of manholes. Do Manholes Open to Outdoors- yes/no indicator. Average Distance Between Manholes- numeric value representing average length (in feet) between adjacent manholes.	Manholes are one way that equipment and personnel enter and exit features like pipelines to perform coatings work. Accessibility into the feature is improved as number of manholes increases. In addition, manholes opening to the outdoors may provide the easiest access for a contractor but could also pose a challenge if environmental conditions are not ideal. Manholes can also represent obstructions that a contractor would have to work around while performing coatings work. Some equipment, like hoses for abrasive blast media or coatings, can enter the pipe through manholes and the work is thus performed in the vicinity of the manhole and is limited to hose length. Distances between manholes can provide insight into accessibility and ease of performing the work or indicate necessary equipment size for the job.
Number of Coats for New Lining	Coating systems can be applied in one or many coats depending on the manufacturer's (or occasionally, the project's) specification.	Numeric value representing number of coats.	Each coat applied on a structure takes a certain amount of time to apply, plus a certain amount of time before additional coats can be applied. Other coating systems may also be multi-coat with each layer needing to be applied in quick succession. Knowing number of coats required (along with specific coating system requirements) is important for planning the work. Systems requiring fewer coats generally take less time in total to apply thus requiring shorter outage periods for the work.
Dry Film Thickness	Total thickness of the applied coating system after it has fully dried.	Numeric value in mils (thousandths of an inch).	This work may identify relationships between coating thickness and coating service lives.
Scroll Case Included	Whether or not the scroll case is included in the recoating work.	Boolean, yes or no indication.	Addition of the scroll case represents added surface area. In addition, the scroll case is a generally more challenging piece of infrastructure to properly

Variable	Definition	Expected Value	Importance
			coat. Coatings applied to the scroll case are subject to more extreme hydrological conditions than the outlet works pipe and tend to degrade or become damaged more quickly.
CP System Included	Whether or not there is a cathodic protection system installed on the feature.	Boolean, yes or no indication.	CP systems generally increase the coating service life. CP system installation also requires additional time, materials, and preparation, and may require usage of certain compatible coating systems.
Number of Outages in Contract	An outage event is one in which the equipment is intentionally configured so that it is not operating so that coatings work can be safely performed.	Numeric value indicating number of times the equipment is "turned off" through the duration of the contract.	A contract may have one long outage or multiple shorter outages over its duration. Number of and length of outages directly impacts stakeholders and water delivery requirements. Project schedule may also be impacted by specific needs.
Number of Outages in Contract	Specific feature or pipe unit number where the work is being performed at a facility.	Specific feature name or unit number where work is performed.	A facility may have one or multiple pipes or features where work is being performed and the feature or pipe must be "turned off" or disabled for use. Large projects may involve multiple outages, i.e., multiple units offline at once or at staggered times.
Return to Service Time	Length of time starting from the time the equipment is taken out of service to when it is returned to service at the conclusion of the job. This value assumes a temperature of 10 degrees C.	Numeric value representing number of days.	Project costs generally increase as number of days that the feature is not is service increases.
All Division CLINs	Total number of contract line items for the work.	Numeric value representing number of CLINs.	Provides an indication on total project complexity.
Division 09 CLINs	Total number of contract line items for Division 09 work.	Numeric value representing number of CLINs.	Number of Div 09 CLINs provides an indication of coatings scope and complexity, with a greater number of CLINs indicating more complex projects.
Division 09 Required Submittals	Total number of required submittals for Division 09 work.	Numeric value representing number of submittals.	Number of Div 09 required submittals indicates complexity of the job. More required submittals may also mean that the job is being closely monitored, is highly important, or has specific complex features that must be closely tracked via many hold points.
Complex Features in Pipe CLIN	A complex feature is defined as croll case, manifold, draft tube, wyes, etc. that cannot be differentiated from the pipe relining cost.	Boolean, yes or no indication.	Complex features inherently cost more due to inability to maintain production efficiency, i.e., higher cost/sqft.
Complex Features Only	Whether the complex feature is the only item in the relining job.	Boolean, yes or no indication.	Relining jobs that include only complex features, such as draft tubes or scroll cases, are less likely to have production efficiencies seen in long stretches of straight pipe, similarly, current robotic application is generally not feasible.
Relining Project or Complex Project with Relining	Whether the relining job has other line items, e.g., water removal from siphon, weld repairs, turbine overhaul, other equipment, or coatings work not captured.	Relining Project = "0" or Complex Project with Relining = "1."	Provides insight into project complexity. Relining jobs may not be the focal point of the overall contract work or they may represent only a small portion of the overall work. This variable attempts to capture these differences, which may provide reduce costs for variable such as mobilization and demobilization, which are spread across more work items.
Scaffolding Cost	Indicates the total cost of materials, construction, deconstruction, etc. of any scaffolding used to perform the coatings work.	Monetary value in USD.	Need for scaffolding indicates large or complex structures. Scaffolding costs can also be a notable addition to total contract cost.

Variable	Definition	Expected Value	Importance
Water Control Cost	Indicates the total cost of materials, construction, deconstruction, etc. of any work related to controlling water to enable coatings work to be performed.	Monetary value in USD.	Provides insight into project complexity.
Hazardous Materials Cost	Indicates total cost involved with hazardous materials work related to the coatings job. Hazardous materials work may involve, but is not limited to, hazardous materials testing of existing coatings and removal and disposal of hazardous waste, among other costs.	Monetary value in USD.	Provides insight into project complexity.