Methods of Relining Penstocks and Pipe Structures: Summary of Collaborative Efforts

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

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Cover Photo: Robotic abrasive blast equipment. (Image reprinted with the permission of Hartman Walsh Industrial Services)

Methods of Relining Penstocks and Similar Structures: Summary of Collaborative Efforts

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Executive Summary

There is an industry-wide need amongst hydropower infrastructure owners and operators to identify improved materials and application methods for penstock relining, evidenced by lining failures and safety incidents over the past two decades. This report documents joint efforts since 2016 between the Bureau of Reclamation (Reclamation) and other government agencies, professional organizations, contractors, and coating manufacturers to advance technologies and promote information sharing to achieve long term corrosion protection of penstocks and other critical piping. The technological focus was on lining materials and robotic relining equipment for large and small diameter pipe in hydropower facilities. Reclamation, the Centre for Energy Advancement through Technological Innovation (CEATI), and other hydropower agencies collaborated on the following highlighted activities.

- CEATI organized a "Penstock Coatings and Linings Workshop," hosted by British Columbia Hydro (BC Hydro) on December 6-7, 2018, CEATI members can log in and view the agenda and all presentations [1].
- Reclamation Science and Technology (S&T) program and Power Resources Office (PRO) project number 19188 produced a best practices "Guide to Recoating and Relining Penstocks and Discharge Tubes" with external reviews from hydropower agencies and CEATI staff [2].
- CEATI members developed a website to exchange case studies of penstock recoating and relining projects, CEATI members can log in and view all case studies [3].
- A cursory economic evaluation of the effect of pipe slope and diameter on the cost of traditional coating application and robotic coating application were included within Reclamation S&T project 19155, Econometrics Analysis and Cost Forecasting for Relining Large Pipes [4].

Collaborations with contractors and coating manufacturers identified technological innovations that are being used for relining penstocks. Contractors reported increased production rates, improved quality, and reduced worker exposure to hazards when using robotic relining equipment [5, 6, 7]. This project also documents the relining of small diameter embedded pipes by a contractor using autonomous robotic equipment [8]. This advancement provided a option for rehabilitating small diameter pipes. Coating manufacturers provided recommended lining materials for large and small diameter pipes at the CEATI workshop [9, 10, 11, 12]. The collaborations helped Reclamation identify three areas in need of future research and development:

- increase reliability and effectiveness during autonomous (unmanned) robotic relining operations by improving equipment monitoring capabilities,
- improve existing robotic technology for autonomous, non-structural pipe relining of small diameter pipes (e.g., less than 18 inches diameter), and
- perform economic study targeting robotic relining technologies; a cost benefit analysis should incorporate the role of improved worker safety and reduced outage duration.

Introduction

Penstocks and discharge tubes are pipes that convey water through the power-generating components in hydroelectric powerplants. They are typically large diameter ranging from three to forty feet, have slopes of zero to greater than 80 degrees, have pressures ranging from 40 to 2000 psi, and lengths varying between 200 feet to five miles, and are essential to the operation of the hydropower plant. These large pipes are often accompanied by small diameter (6-inch to 24-inch) pipe that act as drain, vent, balance, or bypass lines. As with most hydraulic infrastructure, these pipes periodically require recoating and relining. It has been estimated that Reclamation alone will spend $228 million relining its 121 remaining penstocks over the next couple of decades [4].

This report outlines the challenges that hydropower infrastructure owners and operators face with relining penstocks. It will document joint efforts since 2016 between the Bureau of Reclamation (Reclamation) and other government agencies, professional organizations, contractors, and coating manufacturers to advance technologies and promote information sharing to achieve long term corrosion protection of penstocks with a technological focus on lining materials and robotic relining equipment for large and small diameter pipe in hydropower facilities and an emphasis on worker safety.

Challenges with Penstock Relining

Safety

Penstock relining projects can pose a threat to worker safety due to the environment with confined spaces and steep slopes and the potentially hazardous materials that are introduced into the pipe during relining. In 2007, a tragic accident occurred at the Xcel Energy Cabin Creek Generating Station during penstock relining activities [13]. A fire broke out inside the penstock during coating application and five workers died. Preventable factors that contributed to the accident included:

- Poor safety and rescue plans for working in permit required confined spaces.
- Large volumes of solvents for cleaning equipment in the penstock produced a flammable atmosphere within the confined space.
- Large volumes of coating material within the confined space caught fire after the solvent ignited and burned for an extended duration, resulting in a toxic atmosphere.

Material Selection

In 2009, Reclamation was in the planning phase of a relining project at Flatiron Powerplant. Due to the heightened awareness from the Cabin Creek accident, Reclamation's project focused on safety. Coating specialists specified a 100-percent solids polyurethane lining with the intent of pumping materials into the confined space. The pumps were to remain outside the penstocks and solvents were not allowed in the confined space. Construction began in 2010, and the first penstock was put back into service in 2011.

In 2014, cracked lining was noted at sleeve couplings. A 2015 inspection found several 50-foot-long sections of lining had delaminated, originating at the sleeve couplings [14]. There were varying levels of corrosion on the steel surface, with the largest amount of corrosion adjacent to the sleeve coupling. It was assumed that the corrosion lifted the coating, and the high-water velocity peeled the lining off the steel surface.

At the time, it was unknown if polyurethane coating delamination was only a Reclamation problem or if it was industry wide. Reclamation reached out to several utilities, consultants, contractors, and coating manufacturers to determine if there were other instances of lining delamination. Several agencies also experienced polyurethane lining failures, and contractors reported finding failed sections of polyurethane during warranty inspections.

Independent Investigations

Reclamation and Other Hydropower Agencies

Despite the industry-wide impact from the Cabin Creek accident, Reclamation and other agencies began working independently to address the problem of high safety risk during relining projects with the goal of identifying a high-performance, low-solvent coating or new application method that improved safety and provided a quality protective coating. The feasibility of using robotics technologies for relining penstock projects was investigated to limit the need for workers to enter confined space environments. Separately, BC Hydro and Reclamation wrote initial reports highlighting the benefits of using robotics technologies and the status of the current technologies [15, 16]. Some of the benefits recognized were:

- Safer application by limiting the exposure of workers to hazardous conditions.
- Higher quality end products resulting in fewer holidays and rework.
- Shorter outage times to complete work.
- Adaptability to most pipe diameters up to 30 feet in diameter.

Contractors

In addition to the hydropower agencies, contractors were trying to develop safer and more efficient methods for relining projects. Contractors began using robotics for relining pipes in 2009 [5, 6]. At the time, most robotic relining jobs had minimal sloped sections and the work was completed faster than if conventional application methods were utilized. In 2016, a contractor relined a 12-foot diameter discharge tube with inclined sections as high as 77 percent. The ability to use robotics on inclined sections of pipe has allowed for almost any pipe relining project to be completed with increased safety in mind [5, 6, 17].

Collaboration Development

In January 2016, the Central Arizona Project (CAP) consulted with Reclamation for lining recommendations. During the conference call, HDR Inc., CAP, Reclamation, and a contractor discussed the project in detail. After a long discussion regarding the potential for polyurethane linings to delaminate, it was decided to use a 100-percent solids epoxy lining. This team remained engaged during execution of the CAP project, and a collaboration between these agencies resulted for the years that followed.

In July 2016, Reclamation presented to the ASTM International (ASTM) committee D33 Protective Coatings for Power Generation Facilities on the recent polyurethane failure and the needs for improved coatings and linings for the hydropower industry. ASTM D33 membership had strong representation from the nuclear power industry, which has similar structures to hydropower, e.g., large diameter cooling water pipes. The primary difference in hydropower is that the water flow rates and pressures are higher. To better serve hydropower needs, ASTM formed the subcommittee ASTM D33.13 Protective Coatings and Linings for Hydroelectric Power Generation Facilities with Reclamation chairing the subcommittee. The focus for the ASTM subcommittee D33.13 was to develop standards to assist in solving the hydropower industry's coating problems.

Reclamation has been a longstanding member of the Centre for Energy Advancement through Technological Innovation (CEATI), and Reclamation coatings specialists began working closely with them in 2016. CEATI is a large international organization consisting of more than 130 hydropower agencies from 6 continents around the world. At the time, several member agencies were planning penstock or pipe recoating and relining projects, including Reclamation, the CAP, Metropolitan Water District of Southern California (MWD), California Department of Water Resources (DWR), BC Hydro, and Ontario Power Generation (OPG).

In November 2016, Reclamation's coating specialists were invited to speak at a CEATI Penstock Task Force meeting in Seattle, Washington, to present the state-of-the-art coatings and linings for penstocks. They presented case studies of recent Reclamation and collaborator projects utilizing robotics technology and on the premature failures of the polyurethane lining at Flatiron penstocks [2]. During the discussion session, participating agencies concluded there was a need to collaborate and share information for recoating and relining projects to avoid premature failures and improve safety. Three main needs were established to:

- organize a coatings and linings workshop to bring utilities together to discuss specific case histories and experiences with recoating and relining projects,
- develop a guide for recoating and relining penstocks, and
- develop a database for information sharing on recoating or relining projects and detail specific issues or successes of the project.

Following the initial collaborations and relationship development between Reclamation, CAP, HDR Inc., coatings contractors, CEATI, and ASTM, Reclamation's Science and Technology Program and Power Resources Office jointly funded research starting in 2018 to expand collaborations and to develop standards, guides, and manuals for recoating and relining penstocks. A summary of these collaborations and resulting accomplishments follows.

Collaborations through ASTM and CEATI Committees

ASTM D33.13 Protective Coatings for Hydropower Committee

The primary objective for the ASTM D33.13 subcommittee was to develop standards to assist in addressing challenges to the hydropower industry. The subcommittee's first objective was to develop a document listing critical hydropower components and describing their service conditions. Reclamation led this effort, and a draft was developed, however the document was never published. This document breaks down the specific service environment for each component of the hydropower system, the historic coating used, and modern coating systems that could be used as replacement options. Additionally, it lists the ASTM test methods and acceptance criteria for the lining for each hydropower component and service condition that would be required to sustain the environmental conditions. Due to ASTM copyright, Reclamation could not generate a similar manual.

The subcommittee's second objective was to begin developing lining evaluation standards that simulate the service conditions outlined in the critical components document. Specifically, Reclamation's interest was to understand why polyurethane linings prematurely failed in high velocity water [18]. It was unknown if the polyurethane failed based on the material's mechanical and physical properties or if it was due to hydrolysis of the adhesion mechanism. Therefore, to better understand the failure mechanism, research was required to develop a test procedure. In 2019, Reclamation's Science and Technology Program funded the research project 19122, Test Method Development for Adhesion Strength of Protective Coatings under Real-Life Hydraulic Conditions [18]. The initial research made progress in developing a test method and the team is seeking subsequent funding to continue method refinements. Reclamation presented this to the ASTM D33.13 sub-committee, however the subcommittee did not pursue this for a standard due to Reclamation's unique laboratory capabilities, specifically, that most laboratories would not have high head pumps to replicate the test.

Subcommittee D33.13 is now inactive. The subcommittee can reengage the members if further progress on standards for evaluating linings is made.

CEATI Penstock Coatings and Linings Workshop December 6-7, 2018

BC Hydro hosted the CEATI Penstock Coatings and Linings workshop held December 6-7, 2018, in Vancouver, BC [1]. The primary objective of the workshop was to bring together facility owners, consultants, contractors, and coating manufacturers to discuss experiences in recoating and relining penstocks and exchange new technology information and procedures to reline penstocks safely. The workshop's agenda and presentations can be viewed for CEATI members through their website [1]. The workshop consisted of 46 individuals (in-person) from 15 different agencies primarily from Canada, France, and the United States, four coating manufacturers, three consultants, and two contractors. Reclamation had four attendees at the workshop, three coating specialists and one mechanical engineer. Technical sessions included discussion on condition assessments, safety and environmental regulations and procedures, repairs/service life protection of structure, coatings and linings technologies and application technologies, and case histories. Presentations were given by facility owners, coating manufacturers, coating consultants, and coating applicators [1]. The presentations were successful in stimulating conversation, and sometimes debate, among the coating manufacturers. The coating manufacturers recommended using epoxy linings, either solvent-borne or 100% solids, due to seeing failures of polyurethane in high velocity water. Three of the four manufacturers recommended using 100% solids epoxy. There were presentations on robotics applications technologies that highlighted how this technology is changing the way that coatings contractors do business by increasing their production rates, improving quality, reducing worker exposure to harmful chemicals, and decreasing outage time [6, 7]. The safety improvements are magnified by this new opportunity to minimize the number of employees working in permit-required confined spaces.

A Utility Roundtable discussion proved beneficial with agencies prioritizing information exchange of case histories. CEATI committed to setting up a case histories information exchange website portal and developing a best practice guide [3]. Quarterly meetings were set up to make progress on these initiatives.

CEATI Penstock and Gates Task Force Meeting September 17-19, 2019

Ontario Power Generation hosted the CEATI Penstock and Gates Task Force Meeting held September 17-19, 2019, in Niagara Falls, ON. The meeting consisted of 19 attendees from 14 different agencies from Canada, France, New Zealand, and the United States. The primary agenda included the draft template for the case studies information exchange and progress on the guide to penstock coatings and linings. Reclamation attendees included one mechanical engineer and one protective coating specialist. Presentations given by Reclamation included and update of the "Guide to Penstock Coatings and Linings," "Economics Justification and Analysis for Recoating and Relining Penstocks," "Advances in Penstock Coatings and Linings Technologies," and "Use of Robotics Technologies for Penstock Relining."

CEATI Penstock Task Force Virtual Meeting November 5, 2020

The CEATI Penstock Task Force Virtual Meeting was held November 5, 2020. The meeting consisted of 41 attendees from 22 different agencies from Canada, France, New Zealand, and the United States. The primary agenda included the submission process for the case studies information exchange and finalization of the guide to penstock coatings and linings. A Reclamation coating specialist presented the final draft of the Guide to Penstock Coatings and Linings and requested peer review by CEATI members. A presentation was given on "Leak Detection and Penstock Rehabilitation," from Electricite De France (EDF).

CEATI Penstock Task Force Virtual Meeting November 29, 2021

The CEATI Penstock Task Force Virtual Meeting was held November 29, 2021. The meeting consisted of 14 attendees from 11 different agencies from Canada, France, New Zealand, and the United States. The primary agenda included the submission process for the case studies information exchange and providing website for the guide to penstock coatings and linings. A Reclamation coating specialist showed multiple ways to access the Guide to Penstock Coatings and Linings. CEATI also gave a reminder for members to fill out the case studies and upload them to the CEATI Portal. EDF presented on penstock mis-operation.

CEATI Penstock Coatings and Linings Case History Database

CEATI created a library of case studies for coatings and linings projects; the case study questionnaire template can be viewed on CEATI's website [3]. The template allows agencies to share specific details, lessons learned, and challenges with the applications. Six agencies contributed information on ten different relining projects. For the library of case studies, Reclamation contributed five recent relining projects at the following facilities: Elephant Butte Dam, Flatiron penstocks, Glen Canyon Dam, Grand Coulee G7 penstock, and Shasta Dam penstock. Fortum, Placer County Water Authority, Turlock Irrigation District each contributed one case study, and Tacoma Power and California Department of Water Resources both contributed two case studies. The case study jobs primarily used solvent free linings but some solvent-based linings were used due to limitations of pumping plural component linings long distances.

Guide to Recoating and Relining Penstocks and Discharge Tubes

The recoating and relining guide provides facility owners, hydropower plant supervisors, designers, or specification writers a better understanding of the factors that must be considered to achieve cost-effective and safe recoating or relining of penstocks, discharge tubes or similar infrastructure [2]. The guide was led by Reclamation in collaboration with CEATI and other national and international hydropower agencies. The knowledge and experience gained from prior recoating or relining projects from all collaborating agencies provided the foundation for writing this guide [2]. The guide provides detailed information that highlights critical aspects to consider for a successful project, including:

- Expected environmental service conditions
- Existing coatings and linings
- Project planning
- Safety and health
- Hazardous materials mitigation
- Coatings and linings selection and acceptance criteria
- Specification development
- Contractor selection process

Collaboration with Contractors and BC Hydro

State of the Art Robotics Technologies

Robotics abrasive blasting and coating application equipment have been used in efforts for relining pipe since at least 2009 [5, 6]. Initially, most jobs completed utilizing this technology were done on minimal slope. In 2016, a contractor relined a discharge tube with slopes as high as 77 degrees [5]. This was the first known robotics application completed on steep slopes (greater than 30 degrees) and opened the feasibility to reline penstocks with this technology [17]. The robotics technologies reduced the number of contractor employees inside the permit-required confined space, although a few employees were still required to monitor the robots' activities and shut down operations if there was a malfunction.

Between 2018 and 2021, BC Hydro had four penstock relining projects—Bridge River, Puntledge, Cheakamus, and Wahleach Falls—that specified autonomous (unmanned) robotics application for relining penstocks, removing all contractor employees from the permit-required confined space during operation of the robotics [19]. A contractor was awarded these projects and developed technologies utilizing fiber optic cables and a closed-circuit television (CCTV) camera to monitor the robotic application. The initial setup appeared promising, but once the work began on the first project there were significant learning curves with the new equipment, issues with the fiber optic cables being damaged, and the camera lenses being covered with dust during abrasive blasting and overspray during coating application [20]. The contractor's autonomous video equipment was not reliable for monitoring the robot and did not allow for consistent work progress. Each time the autonomous system malfunctioned, production stopped, and workers were required to enter the confined space. A second outage was required to complete the work for the first project [20]. For the second, third, and fourth projects, the contractor continued improving the process and became more efficient on each job [20]. However, the equipment is complex and required engineering support to repair when problems arose.

Two Reclamation relining projects have used manned robotics technologies: Grand Coulee G1-18 penstocks and the John W. Keys III Pump-Generating Plant (Keys PGP) P1-6 and PG7-12 discharge tubes. After relining, only a handful of coating defects (holidays) were found, the product was high quality, and the job was completed safely. Figure 1 shows the final product using robotics application equipment.

In addition, the Keys PGP contractor used autonomous robotics for the small diameter (10 and 12-inch) suction tube bypass filling lines and discharge tube drain lines. The small diameter pipe relining project is described in greater detail in the section below.

Figure 1. Grand Coulee Unit G8 penstock newly applied lining, from the concrete/steel transition to scroll case.

There are some robotics technologies available for field recoating of the exterior of pipe, however it is not known if any coating contractors are utilizing the technology. The possible reason is that there are too many obstacles in the way on the exterior such as saddles, expansion joints, riveted connections, and restrictive access that prevent the use of robotics for the exterior surfaces. Containments are still required when using robotics on the exteriors, whereas the interior pipe surfaces are a containment themselves.

Small Diameter Piping

Small diameter embedded pipe, such as drain lines or bypass filling lines, is extremely challenging to reline. These pipes are typically between 6 and 18 inches in diameter. Therefore, autonomous methods or pipe replacement are the only option. Since these pipes are embedded in concrete, they are not easily replaceable. Refurbishment options are very limited. Table 1 provides the options and details about each. Structural consideration may be needed where embedded pipe exits the concrete and will not be covered in this report.

Table 1. Small diameter pipe refurbishment options.

Pipe Refurbishment Option	**Type**	**Notes**
Replace pipe	Replacement	Requires removing concrete, which can be expensive and invasive
Slip lining with plastic pipe	Pulling a plastic pipe within the existing steel pipe	Limited to straight pipe
Cured in place pipe (CIPP)	Inflating composite pipe within the existing pipe	Different resin types are available for varying structural classes, but inside corner of bends tend to wrinkle and significantly reduce pressure rating
Spray in place pipe (SIPP)	Autonomous	Different resin types are available for either semi-structural or non-structural applications
Primus Line® flexible hose composite	Pulling a woven pipe within the steel pipe	No cure needed after installation; requires an existing flange to attach a spool piece that secures the liner in place
Coat the embedded pipe	Autonomous	Assumes there is adequate pipe integrity remaining

In recent years, several Reclamation facilities inquired to the Technical Service Center (TSC) about relining small diameter piping or other refurbishment options [21, 22]. Due to the challenges listed above, it was uncertain if any of these options would work. Autonomous robotics provide the capability to reline small diameter piping if non-structural refurbishment is acceptable. New technologies may still need to be developed for structural repair of small diameter pipes in dams.

For non-structural repairs, relining was selected as a proactive measure to mitigate the corrosion of the Keys PGP discharge tubes relining project small diameter piping. Figure 2 shows the condition before rehabilitation with significant rust blooms and scale on the interior pipe surfaces [8]. Waterjet cleaning using a small robot was performed and a surface-tolerant epoxy coating was applied using small robotic application equipment. Upon waterjet cleaning, some pipe sections looked fair (Figure 3) while other pipe sections had significant metal loss (Figure 4) [8]. Figure 5 shows the typical pipe section after recoating with the epoxy. Figure 6 shows a screen shot of the CCTV camera feed during inspection further into the small diameter pipes.

Figure 2. Typical small diameter pipe condition before cleaning at John W. Keys III. Pump-Generating Plant small diameter piping. (Image reprinted with the permission of Hartman Walsh Industrial Services)

Figure 3. Typical condition after waterjet cleaning of small dimeter piping at John W. Keys III Pump-Generating Plant. (Image reprinted with the permission of Hartman Walsh Industrial Services)

Figure 4. Significant metal loss of horizontal bypass filling piping at John W. Keys III. Pump-Generating Plant. (Image reprinted with the permission of Hartman Walsh Industrial Services)

Figure 5. Typical condition after two coats of lining in the small diameter piping at John W. Keys III. Pump-Generating Plant. (Image reprinted with the permission of Hartman Walsh Industrial Services)

Figure 6. CCTV video feed after lining application at John W. Keys III Pump-Generating Plant of small diameter piping. (Image reprinted with the permission of Hartman Walsh Industrial Services)

Evaluating the Costs of Relining Using Robotics

Economics can be used to evaluate the cost effectiveness of using manned or autonomous robotics relining equipment. A cursory economic evaluation of the effect of pipe slope and diameter on traditional and robotic coating application were included as a portion of S&T project 19155, Econometrics Analysis and Cost Forecasting for Relining Large Pipes: [4]. The primary objective of S&T project 19155 was to analyze major cost drivers associated with relining large diameter steel pipes and develop a regression model for predicting future relining costs. The project collected data from 73 different relining projects, which were assessed for their varying conditions such as quantity relined, diameter, length, slope, length, location, and whether robotics technology was used. The quantity relined is a major factor in cost per square foot.

The historical project costs analysis allowed for comparison of traditional (manual) application methods to robotics. Figures 7 and 8 show the regression model results for pipe diameter and pipe slope versus cost per square foot, respectively. The model data for robotic and manual application are shown with separate trendlines, and the shaded area is the 95 percent confidence interval. The results indicate that robotic application is cost comparable to manual application for 4- to 12-foot diameter pipes and above approximately 20-degree slopes. Twenty-one-foot diameter was the largest pipe in the data sample using robotic application methods [4]. Therefore, the study recommended not using the model to predict costs of using robotic application methods for pipes large than 21-ft diameter.

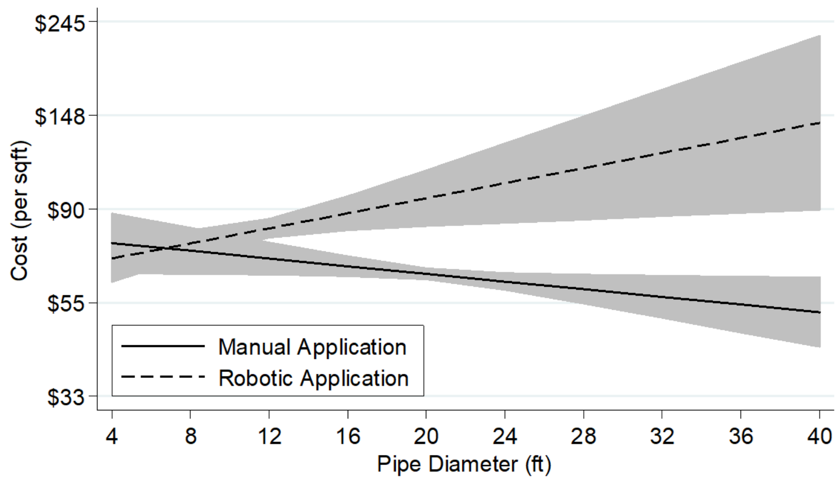

Figure 7. Final regression model predictions of pipe relining costs comparing manual versus robotic application for pipe diameter. Reproduced from S&T report 19155 [4]

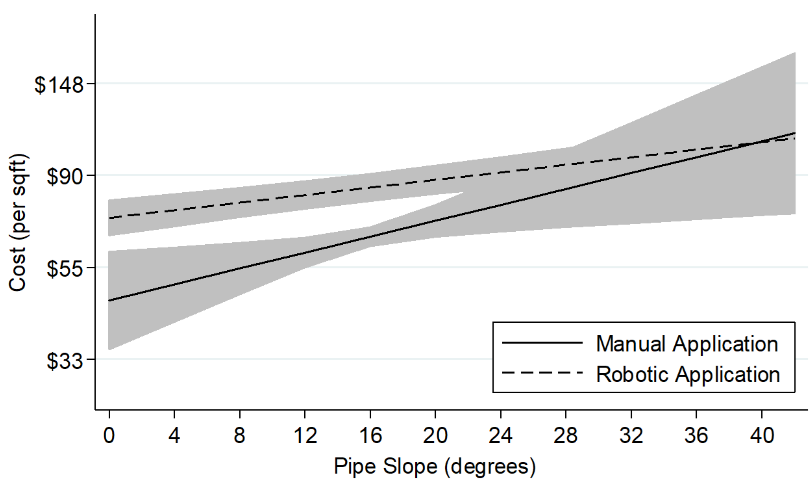

Figure 8. Final regression model predictions of pipe relining costs comparing manual versus robotic application for pipe slope. Reproduced from S&T report 19155 [4]

Figure 8 shows that the manual application cost increased at a steeper rate as pipe slope increases, whereas the robotic application is less influenced by the pipe slope. This steeper rate for manual application could be the result of needing increasingly more scaffolding and equipment to safely perform the work as the slope increases. Robotic equipment is less affected by slope increase, and costs increase at a smaller rate.

Robotics technologies were undergoing development during the period represented in the dataset for S&T project 19155. The project costs may include the initial equipment purchases and time and labor to develop productive methods, which may not be a factor for mature robotics application projects. Future analysis may show cost reductions as this becomes a common relining approach.

The analysis established a framework for future evaluations as new project data becomes available. In addition to continued econometric analysis, a cost benefit analysis should be performed. The cost benefit analysis should incorporate the role of improved worker safety, reduced outage duration, and actual cost to the Government. The econometrics analysis did not conclude that robotic applications provide cost savings to the Government based on historical data, and future cost savings could be realized as the technology matures.

Contractors using robotics on pipes with inclines and large diameters show increased production rates compared to working from scaffolding using manual methods [20]. Recently, on the Grand Coulee penstock relining project, the contractor was able to blast and reline 14,000 square feet in two weeks using robotics, excluding all mobilization, dewatering, and setup [20]. Manual methods require scaffolding and may take a month or longer to blast and reline a structure of this size.

While future economic studies may help to show the cost benefits of robotics technologies, ultimately, safety should be a priority for all jobs. The fewer employees that are in the confined space will result in improved safety and reduced exposure to hazardous conditions. Robotics is now an established approach for reducing the number of employees in confined spaces.

Conclusions

Collaborations between hydropower agencies, contractors, and coating manufacturers have helped advance technologies and information sharing to achieve long term corrosion protection of penstocks. The collaborations helped achieve a more unified approach to recoating and relining projects with increased safety in mind. Advancements through technological innovations in robotic relining allow contractors to increase production rates, achieve better quality and reduce worker exposure to hazards. Most agencies use solvent free linings and robotics technology, eliminating all flammable materials from the confined space work, allowing for a safer work environment.

Collaboration efforts between Reclamation, CEATI, and other hydropower agencies produced the following products:

- A cursory economic evaluation of the effect of pipe slope and diameter on the cost of traditional coating application and robotic coating application were included within Reclamation S&T project 19155, Econometrics Analysis and Cost Forecasting for Relining Large Pipes [4].
- CEATI organized a "Penstock Coatings and Linings Workshop," hosted by British Columbia Hydro (BC Hydro) on December 6-7, 2018, CEATI members can log in and view the agenda and all presentations [1].

- Reclamation S&T and PRO projects produced a best practices "Guide to Recoating and Relining Penstocks and Discharge Tubes" with external reviews from hydropower agencies and CEATI Staff [2].
- CEATI members developed a website to exchange case studies of penstock recoating and relining projects, CEATI members can log in and view all case studies [3].
- A cursory economic evaluation of the effect of pipe slope and diameter on the cost of traditional coating application and robotic coating application were included within Reclamation S&T project 19155, Econometrics Analysis and Cost Forecasting for Relining Large Pipes [4].

The collaborations helped Reclamation identify three areas in need of future research and development:

- increase reliability and effectiveness during autonomous (unmanned) robotic relining operations by improving equipment monitoring capabilities,
- improve existing robotic technology for autonomous, non-structural pipe relining of small diameter pipes (e.g., less than 18 inches diameter), and
- perform economic study targeting robotic relining technologies; a cost benefit analysis should incorporate the role of improved worker safety and reduced outage duration.

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