# OUR CRITICAL ASSETS ARE AGING – A STORY OF RENEWAL OVER REPLACEMENT

*Anna Gibbs (Stantec NZ)*

**ABSTRACT**

The Featherston Street wastewater rising main is a critical pipeline that conveys wastewater flows from the Wellington Central Business District (CBD) to the main Interceptor on The Terrace. The rising main is part of a wider pressure network that services three pump stations in total. Laid in 1947, the aged rising main system had been identified by Wellington Water Limited as being in poor condition and susceptible to failure. At more than 75 years old, the Featherston Street rising main was reaching the end of its useful life and required replacement. However, renewing a 180-metre-long pipeline in the Wellington CBD comes with unique challenges. To manage the impact on businesses, traffic, and the public, the trenchless technology of slip lining was utilised to carry out a successful renewal.

This paper outlines the investigations into trenchless renewal options, the methodology selection process, the material selection process, and the successful management of trenchless installation-related risks. Trenchless technologies are also an effective method of reducing waste and minimising carbon emissions during pipeline construction. This paper explores the benefits of slip lining from an environmental perspective, including calculations that directly compare the carbon emissions associated with slip lining to those produced by the traditional dig-and-lay renewal methodology.

Redundancy had recently been built into the existing rising main system, allowing an online renewal as opposed to needing a new pipe alignment in an area where underground services are densely populated. This paper describes how the renewal methodology was selected, taking into account design criteria, pipe diameters, surrounding services, disruption, as well as contractor technology and experience in the Wellington Region.

Despite its advantages, an online, trenchless pipe renewal posed several technical issues. At more than 75 years old, the existing pipe was cast-iron and therefore subject to tuberculation. Tuberculation are mounds of corrosion that can develop on the inside of a metallic pipe over time. A major concern for the project team was that the new pipe would undergo damage when pulled across these rigid tuberculation nodules during installation. This paper discusses the various mitigation measures the project team explored and successfully implemented to manage the risk of damage during installation and ensure that the final product is free of any defects that could result in a failure before its 100-year design life is complete.

**KEYWORDS**

**Trenchless, slip lining, renewal, carbon**

**PRESENTER PROFILE**

Anna Gibbs is a graduate civil engineer at Stantec New Zealand. She obtained a Bachelor of Civil Engineering in 2020 before studying a Masters of Engineering in Management. Currently based in Wellington, Anna has worked on a variety of projects that have used trenchless technology to renew aging pipelines.

# 1. INTRODUCTION

Stantec New Zealand (Stantec) was engaged by Wellington Water Limited (Wellington Water) on behalf of the Wellington City Council to deliver an upgrade of the Featherston Street wastewater rising main.

Located in the heart of the Wellington Central Business District (CBD), the Featherston Street rising main is a key WWL asset that conveys wastewater flows from the inner city to the Main Interceptor on The Terrace. After years of under-investment, Wellington's wastewater network is aging and under capacity. This has led to large volumes of wastewater overflowing into the harbour and a number of highly publicised pipe ruptures over the last few years, highlighting the increasing need for pipe renewals in the CBD. The Featherston Street rising main was no exception. At more than 75 years of age, the pipeline was in poor condition and in need of replacement.

Renewing a 180-metre-long pipeline in the Wellington CBD comes with unique challenges. To manage the impact on businesses, traffic, and the public, the trenchless technology of slip lining was utilised to carry out a successful renewal. A successful renewal also involved delivering a new pipeline with a 100-year design life. A comprehensive review of methodologies available to the project team was first required to select a suitable methodology based on a variety of factors including performance, constructability, disruption, and cost.

Despite its advantages, an online, trenchless pipe renewal posed several technical issues. Tuberculation present in the existing pipe was a particular concern for the project team as the new pipe could undergo external damage when pulled across rigid tubercules during installation. Various measures were taken to ensure that the final product was free of any defects that could result in the new pipeline failing before its 100-year design life is complete.

This paper discusses the methodology selection process, material selection process, as well as the various mitigation measures the project team investigated and successfully implemented to manage the risk of damage during construction. This paper also explores the environmental benefits of trenchless renewal, including calculations that directly compare the carbon emissions associated with slip lining to those produced by the traditional dig-and-lay renewal methodology.

## 2. BACKGROUND

The Featherston Street rising main is a critical cast-iron pipeline that helps convey wastewater flows from the Wellington CBD to the Main Interceptor on The Terrace. Stretching approximately 180m along Featherston Street between Whitmore Street and Waring Taylor Street, the rising main is connected to the wastewater pump stations (PSs) PS8, PS9, and PS42, as shown in Figure 1. Prior to the improvement works beginning on the PS8, PS9, and PS42 network in 2021, the rising main serviced PS9 by transporting flows from the PS to the common rising main on Waring-Taylor Street and Woodward Street before discharging to the Main Interceptor on The Terrace.

The renewal of the Featherston Street rising main was the second stage of a three-stage programme to improve the condition, capacity, resiliency, and redundancy of the rising main network through this area of the city (connecting PS8, PS9, and PS42 to the Main Interceptor). Due to the condition and capacity issues of the shared rising main, a new 450mm outside diameter (OD) polyethylene (PE) rising main was installed from PS9 with a new connection to the Main Interceptor Tunnel on Bowen Street (Stage 1 of the project). Construction was completed in June 2022. Following construction completion, normal operation sees two of PS9's three pumps directing wastewater from PS9 up the new rising main and one pump sending wastewater down the Featherston Street rising main where it combines with wastewater from PS8 and PS42 at the Waring Taylor Street intersection. An overview of the network after Stage 1 was completed is presented in Figure 1. Stage 3 focuses on renewing the 16-inch cast-iron rising main section along Waring Taylor Street and Woodward Street. This stage is currently on hold and will be completed at a later date.

The exact age of the 14-inch cast-iron rising main along Featherston Street is unknown as the pipeline was originally connected to an ejector station of an unconfirmed age. However, the record drawings for the construction of PS9 dated 1947 show that a new connection from the PS to the Featherston Street rising main was installed when the pipeline was already in service. Therefore, at more than 75 years old, the rising was reaching the end of its useful life and hence susceptible to failure. The existing network had suffered failures in the past, including a high-profile burst on the pipeline servicing PS8 in 2011, just prior to the Rugby World Cup. To combat the risk of additional failures the Featherston Street rising main required renewal.

In November 2022, the pipeline was renewed via slip lining by the Wellington-based contractor G P Friel Ltd, as shown in Figure 2. G P Friel Ltd was allocated the renewal under Wellington Water's contractor panel at the outset of design, enabling a collaborative approach between Stantec and G P Friel Ltd throughout the detailed design phase.

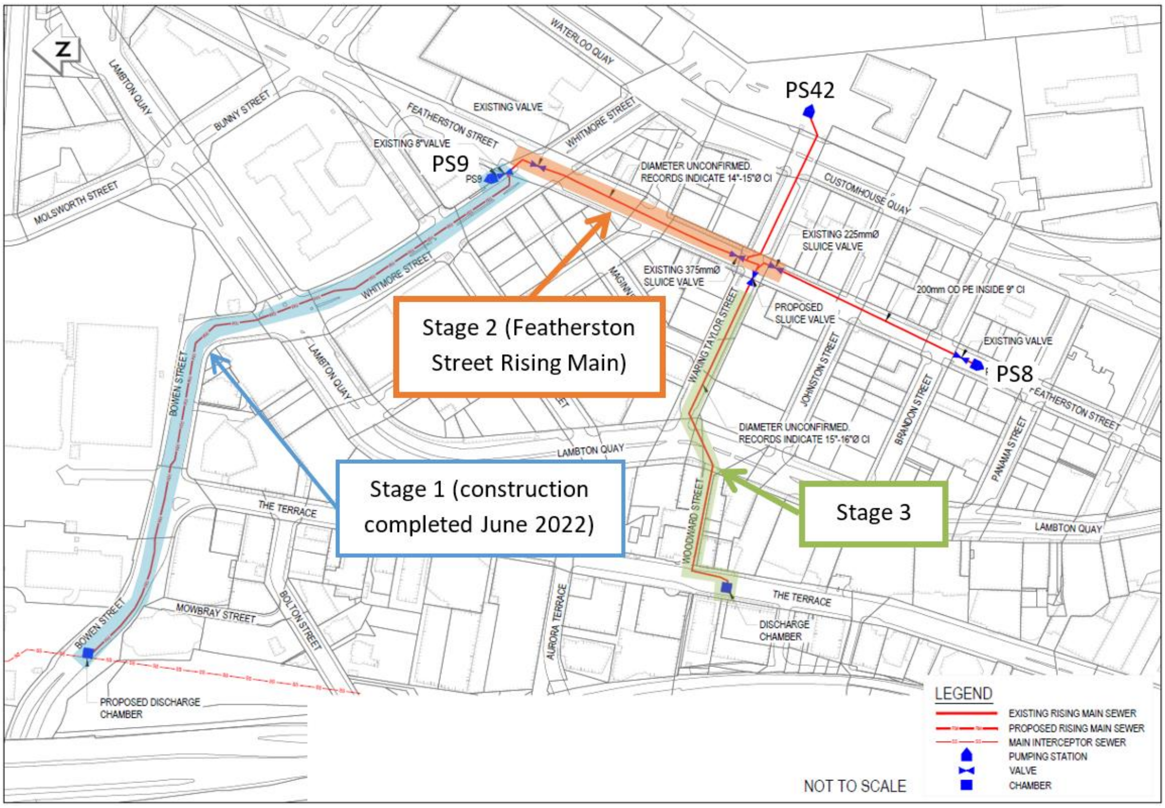


*Figure 1: Overview of the PS8, PS9, and PS42 rising main network and its three-stage upgrade programme.*

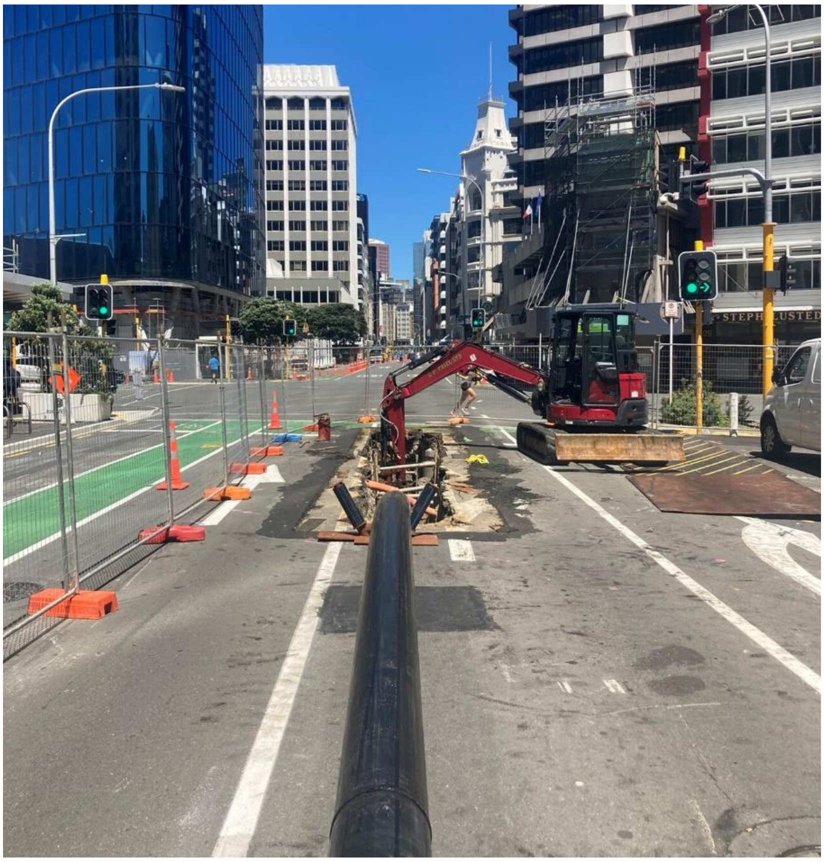

*Figure 2: Installation of the new Featherston Street rising main via slip lining.*

# 3. DESIGN REQUIREMENTS

The project's overall objective was to design and deliver a renewal of the Featherston Street rising main between Whitmore Street and Waring Taylor Street that satisfies the following key criteria:

- Seismically resilient;
- Minimum self-cleaning velocity for the rising main of 0.75 $ms^{-1}$;
- 50-year design horizon for flows; and
- 100-year design life for assets.

# 4. METHODOLOGY SELECTION PROCESS

## 4.1 PRELIMINARY DESIGN

Different methodologies to upgrade the Featherston Street rising main were initially evaluated during the preliminary design, which was completed in 2019. The renewal and replacement options presented in Table 1 were identified and assessed against the following factors:

- Performance against the key design criteria outlined in Section 3;
- Constructability;
- Health and safety;
- Cost;
- Contractor experience and technology available in the Wellington region; and
- Disruption to stakeholders in the Wellington CBD, including road users, pedestrians, and businesses.

*Table 1: Renewal and replacement methodologies considered during preliminary design.*

| Online Renewal Options | Online/Offline Replacement Options |
|---|---|
| Slip lining with PE pipe | Open trenching |
| Close-fit PE pipe lining | Directional Drilling |
| Cured in place pipe (CIPP) pressure pipe lining | Pipe bursting |

The assessment found slip lining to be the most favourable renewal methodology, while open trenching and pipe bursting were considered viable options from a replacement perspective.

Slip lining presented itself as the superior online renewal option as CIPP is not guaranteed to provide a 100-year design life, is more susceptible to quality issues during installation, and is less cost-effective in comparison. The seismic performance of CIPP is also less understood than PE pipe. Close-fit PE pipe lining was not offered by any contractors in Wellington at the time, resulting in slip lining being the preferred online renewal option.

Generally, a key disadvantage of an online renewal relative to replacement is that the network's flow capacity is reduced as a result. This, however, was not applicable in this case as the system had gained additional capacity with the construction of a new rising main during Stage 1. Design calculations confirmed that slip lining the existing 14-inch rising main with a 315mm OD PE pipe would provide sufficient capacity to accommodate the predicted future flows under a fast growth scenario.

Trenchless renewal via slip lining was therefore accepted as the preferred methodology overall as it presented the following benefits in comparison to the other alternatives:

- Minimises disruption to businesses, traffic, and pedestrian movements;
- Eliminates the risk of service strikes along the pipe alignment;
- Allows for adequate capacity to meet predicted growth whilst still providing a 100-year design life;
- Cost-effective compared to open-cut installation;
- G P Friel, the nominated contractor, had the required machinery and experience.

### 4.2 DETAILED DESIGN

Despite slip lining being selected as the preferred renewal method during preliminary design, questions remained around its feasibility. There was uncertainty over the existing rising main's internal diameter and condition. The project team addressed this risk by introducing an alternative "backup" trenchless methodology during detailed design.

The Plastic Pipe Institute Handbook of Polyethylene Pipe (2008) specifies that a minimum difference of 10% between the new pipe's OD and the host pipe's inside diameter (ID) is required to carry out a renewal via slip lining. There was an 11% difference between the existing 14-inch (355.6mm ID) Class D cast-iron pipe and the proposed 315mm OD pipe, satisfying best practice guidelines. Class D cast-iron pipes have the highest specified wall thickness of a 14-inch pipe, and therefore the smallest ID. Hence, there was a low probability of encountering an ID smaller than 355.6mm. It was also considered unlikely that the existing pipe will have a liner due to its age, noting that no liner was found during the slip lining of the PS8 rising main in 2011 which is thought to be the same age. However, the existing pipe's internal diameter had not been confirmed onsite, presenting a risk that slip lining may not be viable due to the inner bore being smaller than what was recorded.

A reduction in ID due to issues with the pipe condition was also identified as a major risk and is discussed further in Section 5.

If the project team deemed the pipe unsuitable for slip lining due to an inadequate annular gap, it was agreed that the pipeline would instead be renewed via static pipe bursting. It was recognised that this methodology introduces risks associated with nearby services. However, as the displacement of the host pipe required to improve the annular gap will be minimal, the risk of heave or damage to nearby services was thought to be low. Clearance from critical services would also be checked prior to construction through potholing. G P Friel had the machinery and equipment required to carry out a trenchless replacement via pipe bursting, confirming this methodology as a viable second option before open-cut replacement would be required which would cause significant disruption to the CBD.

# 5. SLIP LINING RISK MANAGEMENT

## 5.1 BACKGROUND

A major risk identified during design was damage to the new pipe during installation as a result of defects that reduce the internal diameter of the host pipe. The existing rising main had not undergone inspection via CCTV as part of the design process because it could not be suitably shutdown. Therefore, the presence of defects that could prevent a successful renewal via slip lining had not been confirmed. However, at more than 75 years of age, the presence of tubercules within the existing cast-iron pipeline was expected.

Tuberculation are rigid mounds that form on the internal bore of cast-iron and steel pipes through the precipitation and oxidation of corrosion products (Andrianov & Orlov, 2018). A significant project risk was that the new pipe's external surface would undergo damage when pulled across these rigid tuberculation nodules during installation. When pressurised, a PE pipe with external damage such as scratching or gouging can develop slow-moving fractures via the process of slow crack growth (SCG). Over time, SCG causes existing cracks to slowly propagate through the pipe wall until a brittle failure occurs (Hayes, Edwards & Shah, 2015). When in operation, the Featherston Street rising main will be subject to relatively low pressures of approximately 3 bar. Despite this, SCG would remain a risk. While the time to failure will theoretically be longer in comparison to if the same pipe was pressurised to 10 bar, failure can still occur (Brown, 2007).

Damage to the external pipe surface could lead to the new pipeline suffering a burst within 100 years of its installation and failing to meet one of the project's key design criteria.

To mitigate this risk and increase confidence in a successful renewal via slip lining, four primary mitigation measures were implemented:

1. The use of PE100-RC resin for the new pipe;
2. Specifying thorough cleaning & inspection of the host pipe to remove any defects with the potential to cause damage;
3. Pulling a test piece through the cleaned & flushed pipe and inspecting this for defects; and
4. A post-slip line defects inspection of the new pipe.

Centralisers are commonly used within the industry to prevent installation-related damage during trenchless renewals. Centralisers are plastic fittings placed around the new pipe's external circumference that help centralise it within the host pipe and maintain the annular gap during installation (Manouchehri, 2018). These were considered during design, however, when tested during construction, the annular gap proved too small for them to work effectively. Increasing the new pipe's wall thickness was also considered, although this was discounted due to the hydraulic impact.

## 5.2 RISK MITIGATION MEASURES

### 5.2.1 Material Selection

A materials assessment was completed to determine the rising main pipe material considering the installation processes, durability, and cost. During the preliminary design phase, PE100 was selected as a suitable material for the slip lined rising main for the following reasons:

- The material is not susceptible to internal and external corrosion from hydrogen sulphide.
- The material is resistant to degradation from heavy metals present in the site's soil.
- The pipeline uses fully restrained joints which provides good resilience during a seismic event, especially given the elevated liquefaction risk on Whitmore Street, Featherston Street, and Waring Taylor Street.
- The pipe is manufactured in New Zealand (NZ).

During detailed design, an alternative HDPE resin, PE100-RC, was identified as a potential material to help mitigate against trenchless installation risks. PE100-RC, or PE "Resistant to Crack", is pipe produced from High Stress Crack Resistant resin. By employing hexene as the co-monomer rather than butene, as is used in most PE100s, PE100-RC's molecular structure has longer side branches which results in stronger tie molecules that can withstand crack propagation (Shore & Wedgner, 2014).

For the following reasons, PE100-RC was considered a suitable material for this project, in addition to those outlined for PE100 above:

- The material has superior resistance to SCG and reduces the risk of premature failure as a result of installation-related damage. Research indicates that the time to failure of PE100-RC pipe samples due to SCG is approximately 10 times longer than standard PE100 (Shore & Wedgner, 2014).
- The material was readily available in NZ and is offered by two primary suppliers: Hynds and Asmuss.
- There was a minor cost premium of 3% - 5% for PE100-RC compared to standard PE100.
- The material's welding and testing properties are compatible with those of PE100. Hence, PE100-RC can be welded to PE100 without sacrificing weld

strength or constructability. This is supported by the fact that all pre-construction weld tests yielded ductile results.

In European markets, pipe manufactured from PE100-RC resin is tested to ISO 4427 to confirm the “RC” component meets minimum performance requirements. Discussion with local PE suppliers confirmed PE100-RC would meet the client, Wellington Water’s, technical specification requirements to conform with NZS 4130 and NZS 4131. However, there was no approved test in NZ to certify the crack resistance performance. Therefore, while it was considered that the use of PE100-RC resin was highly likely to provide a significantly more crack resistant pipe than standard PE100, a disadvantage was that it could not be locally verified against any sort of minimum performance standard.

5.2.2 Host Pipe Cleaning & Inspection

Thorough cleaning & inspection of the host pipe was specified in the contract to remove any defects with the potential to cause damage and ensure the pipe was returned to its original bore. Standards and specifications published by international water bodies were reviewed to identify methods that have been successful on projects overseas and inform the final regime.

To prepare the host pipe for slip lining, it underwent several iterations of mechanical scraping, flushing, and CCTV inspections. A CCTV inspection of the pipe was carried out before cleaning commenced. The internal diameter was measured at 350mm. The annular gap the host pipe would form when slip lined with a 315mm OD pipe would therefore satisfy the limits recommended by Plastics Pipe Institute. However, as shown in Figure 3, tuberculation was present inside the existing cast-iron rising main, to a degree where damage to the new pipe could be expected.


*Figure 3: Internal condition of the existing cast-iron Featherston Street rising main prior to cleaning.*

To remove the tuberculation nodules from the internal walls, the contractor, G P Friel Ltd, first pulled a mechanical scraper through the host pipe using a winch. The scraper used, as shown in Figure 4, was not commercially sourced but fabricated by G P Friel Ltd for this cleaning. G P Friel Ltd continued pulling the scraper through the pipe until the winch's pressure log indicated that the instrument was no longer meeting any major resistance. This was achieved after two passes of the pipe's full length. Figure 5 shows that the scraper successfully removed the large tuberculation nodules from the pipe's full circumference, however, tuberculation debris remained on the pipe invert. This was flushed from the pipe using high-pressure jets, which simultaneously removed the layer of corrosion deposit that was still present on the walls. Several passes of the jet were required to flush the pipe clean in preparation for renewal. The host pipe's internal condition after cleaning was inspected via CCTV and, as can be seen in Figures 6 and 7, no significant defects were identified.

*Figure 4: Mechanical scraper fabricated by G P Friel Ltd.*


*Figure 5: Internal condition of the existing cast-iron Featherston Street rising main after two passes of the mechanical scraper.*


*Figure 6: Internal condition of the existing cast-iron Featherston Street rising main after being flushed clean by a high-pressure jet (CH 4.82m).*


*Figure 7: Internal condition of the existing cast-iron Featherston Street rising main after being flushed clean by a high-pressure jet (CH 73.17m).*

5.2.3 Test Piece

To confirm no significant defects remained in the host pipe after cleaning, G P Friel Ltd pulled a three-meter section of 315OD PE100-RC SDR17 pipe along the full slip line alignment. The walls of this test piece were inspected for gouges that exceeded the 2mm tolerance as per the Wellington Water Specification for Water Services. No measurable defects were identified, as all markings had a depth of less than 0.5mm. This indicated that the pipe's bore was free of any material that could cause notable damage to the new pipe during installation. The test piece's external condition post-slip line is presented in Figure 8.

*Figure 8: External condition of the three-meter long test section post-slip line.*

5.2.4 Post Slip Line Defects Inspection

After confirming no significant gouges were present on the test piece, 180m of 315OD PE100-RC SDR17 pipe was slip lined through the existing cast-iron rising main with the winch set to a maximum pulling tonnage of 4.2 tonnes. This is well below the new pipe's maximum pulling force, calculated to be 14.7 tonnes. An increase in the set point for the winch pull tonnage was not required at any point throughout the installation, indicating that the new pipe did not meet major resistance while in contact with the host pipe.

The first five meters of pipe could be accessed in the reception pit for inspection after the slip line was complete. This section was inspected as it should theoretically bear the most damage compared to the remaining 175m of pipe. This is because it is in contact with the host pipe over the full 180m alignment. A section of pipe located halfway along the alignment would only travel half the distance and hence not come in contact with all defects present in the host pipe. The new pipe's external condition post-slip line is shown in Figure 9. The post-slip line inspection found that the markings on the pipe were predominantly superficial scratches that could not be measured. No gouges that exceeded the 2mm tolerance specified were found to extend into the host pipe. Based on these findings, the new pipe was accepted for installation.

*Figure 9: External condition of the new pipe post-slip lining (top of pipe).*

# 6. ENVIRONMENTAL BENEFITS OF TRENCHLESS CONSTRUCTION

Faced with the growing threat of climate change, the water and construction industries are under increasing pressure to deliver more sustainable solutions while still meeting design requirements. It is widely known that, in the pipe renewal space, trenchless construction is a sustainable alternative to traditional open trenching as trenchless technologies have significant potential to reduce the greenhouse gases emitted during a pipeline's construction. Trenchless pipe laying generates carbon savings by minimising the amount of time equipment is used, the volume of excavated material hauled from the site, the volume of backfill material transported to the site, and traffic delays in urban areas (Beale et al., 2015).

This notable benefit of trenchless construction was not identified during the methodology selection process carried out for the Featherston Street wastewater rising main renewal project in 2019. To highlight the carbon-reduction potential of trenchless technologies, the carbon emissions associated with renewing the Featherston Street rising main via slip lining, static pipe bursting, and open trenching have been calculated. This was done using an internal Stantec carbon assessment tool. The results are presented in Table 2.

*Table 2: Total estimated construction-related emissions associated with different renewal/replacement methodologies.*

| **Renewal/Replacement Methodology** | **Total estimated construction-related carbon emissions (tonnes $CO_2$eq)** |
|---|---|
| Slip lining | 14.06 |
| Static Pipe Bursting | 16.2 |
| Open Trenching | 39.8 |

Comparing the values shown in Table 2, slip lining has the lowest carbon impact of the three options, while the traditional dig-and-lay methodology has the highest. These results suggest that the selection of a trenchless renewal methodology on this project resulted in 65% less, or 25.7kg$CO_2$eq less, carbon being emitted to the atmosphere during construction. If the pipeline was alternatively renewed via static pipe bursting, this would have led to an estimated 23.6kg$CO_2$eq less carbon being produced during construction. Trenchless technologies are therefore a valuable carbon-reducing initiative that can be utilised in a project, and carbon impact is a notable factor that should be considered when evaluating the methodologies available on a project.

## CONCLUSIONS

The Featherston Street wastewater rising main is a critical Wellington Water asset that was successfully renewed via slip lining in November 2021. During the design, a comprehensive methodology selection process was carried out to identify the preferred renewal methodology of slip lining for the project. This methodology was selected as it provided the following benefits:

- Minimises disruption to businesses, traffic, and pedestrian movements;
- Minimises the risk of service strikes along the pipe alignment;
- Allows for adequate capacity to meet predicted growth whilst still providing a 100-year design life; and
- Cost-effective compared to open-cut installation.

Many of these advantages are also shared with other trenchless technologies available in the Wellington Region. A significant benefit of trenchless renewal not considered during the methodology selection process was its potential for reducing carbon emissions during the construction phase. Carbon accounting calculations show that slip lining the existing Featherston Street pipeline instead of replacing it via open trenching reduced the construction-related emissions by 25.7kg$CO_2$eq or 65%. In the water industry, the expectation for designers to facilitate better carbon outcomes on projects is steadily growing. This project highlights the importance of considering the carbon impact of methodologies during the selection process as there can be significant differences.

Renewing a 75-year-old cast-iron pipe via slip lining also comes with additional risks that require management. The project team implemented several mitigation measures to ensure a successful slip line renewal could be carried out while still meeting the key design objectives. These are as follows:

1. The use of PE100-RC resin for the new pipe;
2. Specifying thorough cleaning & inspection of the host pipe to remove any defects with the potential to cause damage;
3. Pulling a test piece through the cleaned & flushed pipe and inspecting this for defects; and
4. A post-slip line defects inspection of the new pipe.

This project demonstrates that designers in the water industry should not be deterred by additional challenges associated with trenchless methodologies, as their benefits can be realised more often than they currently are. With proper understanding of the risk, and preparation and planning, the risks can be effectively managed to ensure more successful trenchless pipe renewals are carried out.

Investigations into the feasibility of different methodologies during detailed design showed that alternative trenchless technologies should also be considered before resorting to open-cut installation. Taking the extra steps to increase confidence in trenchless renewals will ensure these technologies, and their benefits, are seen more widely throughout the industry.

## ACKNOWLEDGEMENTS

I would like to acknowledge the following:

- The Stantec New Zealand design team, James Mabin and Yassasvie Sundarapperuma.
- G P Friel Ltd and in particular Gerry Friel and David Philipson.
- Wellington Water and in particular Sean de Roo, Paul Winstanley, Gerry O’Neill, and Tim Strang.

## REFERENCES

Andrianov, A. and Orlov, E. (2018), ‘Explanation of tuberculation scales formation in steel and iron pipes using the theory of wave motion of a liquid’ *MATEC Web of Conferences, 178, 04002.*

Beale, D., Gould, S., Lane, B., & Marlow, D. (2015) *‘Rehabilitation of small-diameter cast-iron pipe: US, UK, and Australian perspectives’* Journal - American Water Works Association, 107, 1, E12-E21.

Brown, N. (2007), ' Intrinsic Lifetime of Polyethylene Pipelines’ Polymer Engineering and Science, 47, 4, 477-480.

Edwards, D.B., Hayes, M.D., and Shah, A. R. (2015) *Fractography in Failure Analysis of Polymers,* Elsevier, Waltham, 48-110.

Manouchehri, S. (2018), 'Considerations in Design of Centralizers for Pipe-In-Pipe Systems' *ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering, Madrid, Spain, 17-22 June.*

Plastics Pipe Institute. (2008) *Handbook of Polyethylene Pipe,* 2nd ed., Plastics Pipe Institute, Texas, 397-420.

Shore, A. and Wedgner, A. (2014), 'Why Replace Existing Pipelines When They Can Be Rehabilitated Using Polyethylene Pipes and Fittings' *Water New Zealand Conference & Expo,* Hamilton, New Zealand, 17-19 September.