Technical Note 10 – Effect of Deterioration on Seismic Resistance of Underground Pipelines Systems

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1 Background

Common sense indicates that corrosion would make a buried pipeline more vulnerable to seismic damage in the event of an earthquake. This paper aims to establish how significant the effects are.

2 Corrosion

The Australasian Corrosion Association website (corrosion.com.au) states:

> *"Corrosion can be defined as the destruction or deterioration of a material through reaction with its environment. The term "corrosion" can refer both to a process or the damage caused by such a process."*

Most pipeline materials corrode:

- Metal systems: Cast iron, ductile iron and steel; copper and galvanized steel;
- Cement based systems: concrete, reinforced concrete, asbestos cement, and factory or site-applied cement or concrete linings;
- Coatings, linings and fittings, sealing rings etc can corrode or degrade.

Some pipeline materials - Ceramic pipes (earthenware, vitreous clay) and plastics (PVC, PE and GRP) - do not corrode in normal conditions, but can be degraded when exposed to severe chemical or environmental conditions. However, even though these materials do not corrode as such, associated fittings and sealing rings can and do corrode.

2.1 Types of Corrosion

Most corrosion either removes material (eg rusting of steel) or it converts a material from one form to another that has different properties (eg Asbestos Cement, cast iron and concrete).

Two broad classes of corrosion are considered here:

- General corrosion which affects a broad area, but with some variation from place to place. This includes general loss of steel, graphitisation of cast iron and degradation of the binder in cementitious materials, notably asbestos cement;
- Local corrosion in which the effect of corrosion is highly localised. In many cases local corrosion will affect only parts of a component and nearby areas may be almost uncorroded. Local corrosion usually progresses much faster than general corrosion.

The two can occur together.

General corrosion has a number of potential effects that can make failure more likely and make repairs more difficult:

- It reduces load bearing section of the corroding component. In a pressure pipeline this reduces the resistance to the internal operating pressures as well as reducing the capacity to withstand transient loads such as seismic loads and any related pressure surges. In a gravity pipeline it reduces the ability of the pipeline to support itself, making it more reliant on external soil support and bedding factors;

- Reduced thickness can make welding more difficult and a thinned pipe wall may no longer be able to resist compressive sealing forces from a gibault style compression fitting;

- The roughened corroded external surface may be rough enough to make it more difficult to create or maintain a compression seal to the outside of the pipe.

Local corrosion typically takes the form of isolated points of corrosion (pitting) or small areas where conditions encourage corrosion (under deposits, in narrow gaps). The effects are different from those of general corrosion:

- Perforation of a pipe wall can resulting in leakage but with no or minimal structural impact;

- It can create local stress concentrations that increase likelihood of failure under high stress;

- It can undermine seal integrity either through creation of a leak path under the seal or when water escaping from a leak damages the sealing ring.

While isolated failures may have an important impact through leakage, repair of local corrosion damage may be relatively simple if a clamp or patch repair can be used or if a damaged section of pipe can be cut out and replaced.

2.2 Effects of Corrosion

The impact of deterioration can be different for gravity and pressure systems. In a pressure system, the pressure acts all along and around the pipe, so failure can usually be expected at the weakest point wherever it is. However, fully degraded pipes with negligible remaining strength can occasionally remain serviceable if the surrounding soil provides sufficient support to prevent failure (Figure 1).

A concrete lining can prevent leakage from a steel pipeline even when the steel has perforated (Figure 2). While a brittle concrete lining could be expected to fail more readily than the ductile steel pipeline it is lining, evidence from Christchurch shows that concrete linings can remain bonded and relatively undamaged when steel is subjected to seismic loads (Figure 3). Laboratory tests have confirmed that linings can remain bonded even when the pipe is severely deformed (Figure 4).

In contrast, the load in unpressurised systems varies around the perimeter and for gravity flow systems installed at grade it can also can vary along the length. As a result, a local weak point may not be subjected to high loading. In some cases the soil is self-supporting and a completely degraded pipe may remain functional until the surrounding soil collapses (Figure 5).

Degraded gravity pipelines that fail due to overloading can sometimes continue to operate as flexible pipelines. Observations from the UK during research into sewer repair systems (Morris, 1989 to 1999) indicated that some rigid earthenware pipelines that had experienced a four-point break due to construction loads had continued to operate as flexible pipelines for approximately 60 years. Figure 6 shows how an AC pipe could potentially remain serviceable as a flexible pipe after compressive overload.

3 Structural Effects of Corrosion

The effect of corrosion on structural performance differs mainly with the form of corrosion that affects the pipeline material.

3.1 Steel

Steel along with ductile iron and copper typically corrode through a combination of rapid local pitting and slower general corrosion. These metals have high strength and therefore usually have relatively thin walls.

A typical steel water pipeline will experience areas of general corrosion that include areas of more severe local pitting corrosion. Pitting corrosion rates for steel and ductile iron in soil are typically around five times greater than the general corrosion rates. In potable water and fresh river water, pitting corrosion rates are usually about 3 to 5 times the rate of general corrosion (Shrier, 1994).

Because pitting corrosion is so much faster than general corrosion, local perforation will normally occur well before substantial general corrosion has occurred. Fracture mechanics analysis to AS/NZS 3788 indicates that in most metallic water pipelines, perforation will always occur well before the pipe is at risk of breakage which confirms this expectation and matches what is observed (Figure 7 to Figure 10).

Since most water utilities conduct some form of active leakage management programme, the majority of modern steel, ductile iron and copper pipelines will be removed from service due to leaks well before structural integrity is threatened.

While pitting removes metal from the wall of metal pipes, the corrosion product formed occupies a greater volume than that of the metal consumed. This is readily apparent in smaller bore steel and iron pipelines where internal corrosion products expand into the pipe, blocking the bore (Figure 11). The corrosion product can also block individual perforations, which will either prevent leakage entirely or restrict the leak to a minor weep. In normal service, continued corrosion of the surrounding metal eventually exceeds the bridging ability of the plug of corrosion products causing the leak to become apparent (Figure 12). Where a seismic load dislodges a plug of corrosion product, it has brought forwards the failure rather than caused it.

In the case of older steel pipes, failure can occur at riveted, lockbar or gas welded seams and along lap welded joints (Figure 8). These are points of inherent weakness within the pipeline and corrosion is not required to cause failure, although it may increase the likelihood and extent of failure.

3.2 Asbestos Cement (AC) Cast Iron and Concrete Pipes

While the detailed corrosion mechanisms are different, corrosion changes the original materials into a weaker form, rather than removing material or creating perforations. The loss of strength caused by corrosion then leads to a higher risk of failure.

Peak deterioration rates in these materials are typically about 50% faster than mean corrosion rates, which is a much smaller ratio than the difference between pitting and general corrosion in steel. As a result, AC and Cast Iron pipelines usually experience structural failure rather than perforation. Since seismic events can generate additional ground loads and pressure surges, they can overload weakened pipes that could have remained serviceable in normal operating conditions.

Figures 15 to 18 show seismic failures that are indistinguishable from in-service failures. All of the pipes shown were heavily degraded, and a small additional load (whether from operational loads or seismic load) triggered the same form of failure.

Much as with dislodged corrosion plugs, the presence of corrosion contributes to failure but the earthquake brings it forwards rather than creating a failure that would not otherwise have happened.

A similar situation will occur in cast iron pipelines, except that because even a fully degraded pipe they can withstand normal service pressure (Figure 19), there is a possibility that seismic events can cause failures that would not occur in normal service.

3.3 Plastics and Other Materials

Some pipeline materials (Earthenware, PE, PVC and GRP) do not corrode in normal service, but can be degraded when exposed to severe chemical or environmental conditions. Because these are unusual cases, they are not representative of the system. However, even though these materials do not corrode as such, associated fittings and sealing rings can and do corrode.

3.4 Types of Failure where Corrosion has Limited Effect

Beam bending failures can occur in smaller diameter pipelines with a high length to diameter ratio even when new. This means that the pipe does not need to be corroded to fail in bending (Figure 20). Failures of joints due to lateral displacement or bending are also largely unaffected by deterioration as they can occur whether the collar is corroded or not (Figure 21). As noted above, the form of deterioration usually means that by the time a pipe is structurally weakened, it will usually have been at risk of failure for some time. However, it is also possible for fittings with severely corroded bolts to remain serviceable for some time, even when exposed to earthquakes, (Figure 22).

Observed failures from Christchurch show failures in AC pipelines that involve fracture of joint sockets, tensile failure of joints through separation, compressive failure of joints. While deterioration will reduce the resistance of sockets to fracture, it has no bearing on tensile resistance of joints and is not required for beam bending to occur. Evidence from tests on concrete pipes indicates that joint installation practices can have a greater impact on compressive joint resistance than corrosion could. So while deterioration does increase the risk of pressure related failure during a seismic event, failure is inevitable anyway, and the earthquake has merely brought forwards the time of failure.

Crushing failures are rare in service, and analysis of crushing test records from the Opus pipeline database indicates that failure will not normally occur until the crushing strength is less than 35% of the contemporary specification value (Figure 23, Figure 24). A pressure pipe in this condition will have lost its ability to withstand normal service pressures many years previously and will have been replaced, although in principle a gravity systems could remain serviceable.

3.5 Cathodic Protection

Where a pipeline is cathodically protected (Figure 25) further corrosion is stifled for as long as the system can provide sufficient protective current. The pipeline shown in Figure 25 was found to be corroding following partial exposure of the pipeline in a major storm in the 1980s, and the corrosion state has remained unchanged since a cathodic protection was installed soon after. Despite moderate corrosion, no failures occurred when the system was affected by a substantial earthquake in 2007.

Damage to a cathodic protection system will result in delayed failure if not detected and repaired, since corrosion will reactivate and eventually lead to perforation or loss of structural strength. A similar effect will occur when any corrosion protection system is damaged. However, impressed current cathodic protection systems can be inspected non-destructively to check if they are working and to establish how much protection they are providing, so it is more practical to locate and repair defects that is the case with passive corrosion protection systems such as coatings.

4 Effect of Corrosion on Repair

Severe corrosion can make repair more difficult. Where corrosion has affected the structural integrity, the damaged pipeline may lack the strength to support the sealing pressures applied by the rubber seal in a repair clamp or collar.

In a related problem general corrosion of the outer surface of some pipes (notably, AC and steel) may result in a rough surface that cannot sustain a seal even when the pipe wall has sufficient strength to support the applied loads.

Severely thinned steel pipe walls become increasingly difficult to weld.

In all of these cases, defective sections may need to be removed until a sound pipe surface is reached. This can result in tens of metres of pipes being replaced following a single pipe burst in normal service (Morris 2016). Similar cases could be expected when failure is triggered by seismic loads.

5 Apparent Corrosion

PVC pipelines provide an example of how technological change can create the appearance of degradation. When PVC was introduced in the UK on a large scale in the 1960s, materials quality was generally quite low and high levels of failure were observed in some pipelines (Kirby, 1981). While installation and operating practices were important factors, fracture toughness (a measure of the ability to resist catastrophic failure when cracked) was quite variable with a typical maximum of about 2.75 $MPa.m^{1/2}$ in a well-made pipe, but considerably lower in poorly processed pipes (Morris, 1993 to 1999).

Over time, improvements were made to processing, which in turn resulted in improved dimensional stability and progressively increasing toughness. In 1986, for example, a minimum toughness of 3.25 $MPa.m^{1/2}$ was introduced in the UK (BS3505), and by the mid-1990s, the UK Water Industry Specification WIS-31-06 required values of 3.25 $MPa.m^{1/2}$ to 5 $MPa.m^{1/2}$ according to the pipe wall thickness. At the higher levels of specified fracture toughness, the practical toughness of PVC-U is approaching the level where it behaves as a fully ductile material.

Within New Zealand, similar product improvements have been observed, although the dates and drivers for change have been different. However, manufacturing defects such as poor wall thickness control and inclusions that were seen in pipe made in the mid and late 1980s are almost unheard of now due to improvements in manufacturing practices and quality control.

Similar patterns are seen in steel pipelines where production practices have changed. The earliest steel pipes were produced by riveting sheets together or using a lockbar. When welding was introduced, early gas welding was difficult to control and was later replaced with more efficient and reliable electric welding. In addition, early lap welding could allow cracks to travel along the seam, causing long lengths of pipe to split when there was a failure (Figure 7 and Figure 8) while more modern butt welding systems are more robust, as the weld is no longer a major point of weakness. US sources show clear distinctions in the observed break rates and treatment of steel pipes fabricated using different welding techniques.

There have also been changes to sealing technology that influence joint integrity and tolerance to displacement.

These technological changes create a genuine difference in behaviour over time. Because of the trend towards improved systems behaviour, it can appear that older systems have degraded. While there are occasions where the degradation is real, it is often a false impression attributable to technological improvements.

6 Summary

The key point to take from this is that corrosion can reduce the ability of pipeline systems to withstand loads and pressures, which can potentially degrade its seismic resistance. However, many of the reported examples of the effect of corrosion on observed break rates actual relate to improvements in materials manufacturing practices and installation practices over time rather than to degradation of the material in service.

Many traditional materials degrade over time. In most cases, degradation can be expected to reduce the tolerance to seismic loading by weakening joints or reducing load bearing sections of the pipelines themselves. However, many pipelines that are affected by corrosion were also vulnerable to seismic damage even when new.

While corrosion does weaken pipeline systems in ways that increase vulnerability to seismic loads and any resulting surges, other factors such as change in technology can account for some of the reported effects of corrosion. The role of corrosion in seismic failures may be overstated because while corrosion may increase the likelihood of failure or the extent of damage, seismic failures can also occur whether there is corrosion or not.

7 Conclusions

- Some corroded pipeline systems are more vulnerable to failure during seismic events, but corrosion does not necessarily result in failure during an earthquake;
- The systems most likely to be affected by corrosion typically have inflexible pipe barrels and joints with limited capacity to accommodate movement, so they have poor seismic durability even when new and uncorroded;
- In most cases, seismic events bring forwards failure of corroded pipelines that would have otherwise failed in service in the future, rather than causing a failure that would not have occurred in normal service;
- Corrosion can increase the severity and extent of a failure and can limit repair options;
- Ongoing improvements to product specifications, manufacturing practices and installation practices can give the impression that pipelines are degrading over time, when in fact newer ones are simply being made and installed to a higher standard;
- Seismic damage to corrosion protection systems will allow corrosion to initiate or to restart and will lead to future failures in normal service if not identified and repaired. These delayed failures would be caused by the earthquake even though the failures will occur in normal service.

8 References

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WIS 4-31-06 (1994), 'Specification for blue unplasticized PVC pressure pipes, integral bends and post-formed bends for cold potable water (underground use)'.

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J Morris and J Boot, "Renovation using thin walled plastic liners", Pipeline Systems, May 1994, Edinburgh, UK.

J Morris, client discussion on an AC pipeline repair, 2016.

The following images show examples of corroded pipes, including pipes that failed in service and pipe that failed in a seismic event and examples where the form of failure is unrelated to corrosion.

Figure 1: DN50 Asbestos Cement pressure pipe that remained serviceable for several years due to support from the surrounding soil despite being fully degraded.

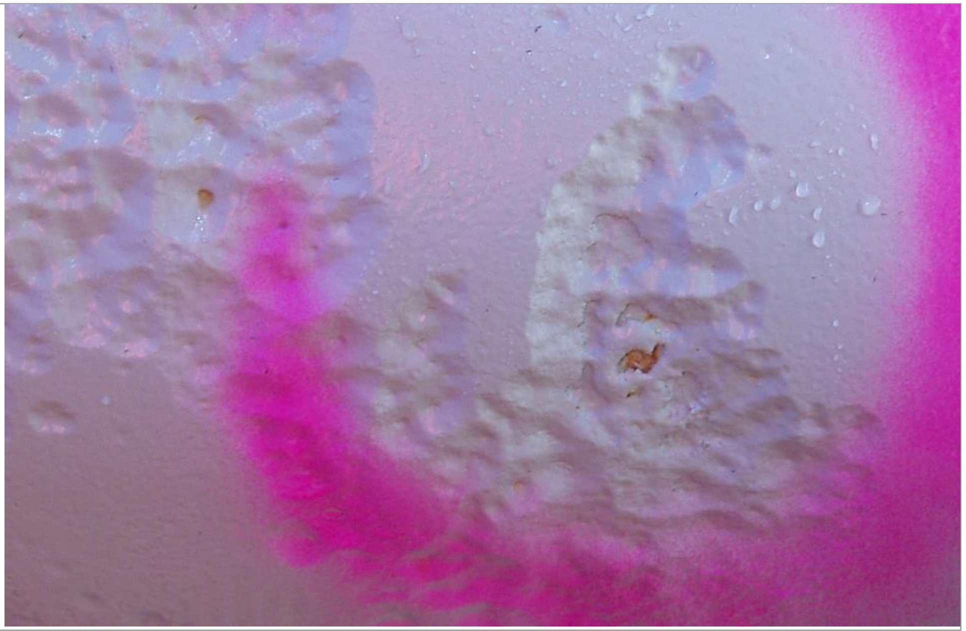


Figure 2: Concrete lining showing through perforated steel after blasting in preparation for re-coating in 2014. The perforation is approximately 6 mm in the largest dimension. The line was cathodically protected in the late 1980s, so the perforation was present before then. The combination of a plug of corrosion product and concrete lining has minimised any leakage in perforations up to at least 15 mm across.

Figure 3: Concrete lining in a steel pipe subjected to seismic loads and a pre-existing perforation. The perforation has probably been present for decades and was either blocked by corrosion product or was not detected because it leaked into the body of a gibault coupling.

Figure 4: Parts of the concrete lining have remained bonded to the steel despite severe compressive deformation of the pipe during testing.

Figure 5: The black channel is the remains of and AC wastewater pipe that had remained serviceable for years in stable soil after total destruction of the cementitious binder in aggressive conditions. The thicker collars still remain present. The damage was only detected when a pipe above them collapsed.

Figure 6: AC pipe after testing in compression. Despite experiencing a four point break, the pipe is still capable of performing as a flexible pipeline for at least a short time.

Figure 7: Perforation in a steel pipe. This pipe was recovered from service as part of condition assessment programme. The perforation was located just inside the outer edge of the gibault sealing ring and had remained undetected in service for many because the space between the pipe and gibault was blocked by corrosion product.

Figure 8: Perforation next to a gibault fitting in a DN600 Concrete lined steel pipeline. The leak was discovered after the seismic events but the perforation had been in place for some years. It is possible the leak had been blocked by a plug of corrosion product that was displaced by the shaking.

Figure 9: DN63 galvanized steel water pipe with deep perforations. Structural capability was unaffected despite the relatively large size of the holes.

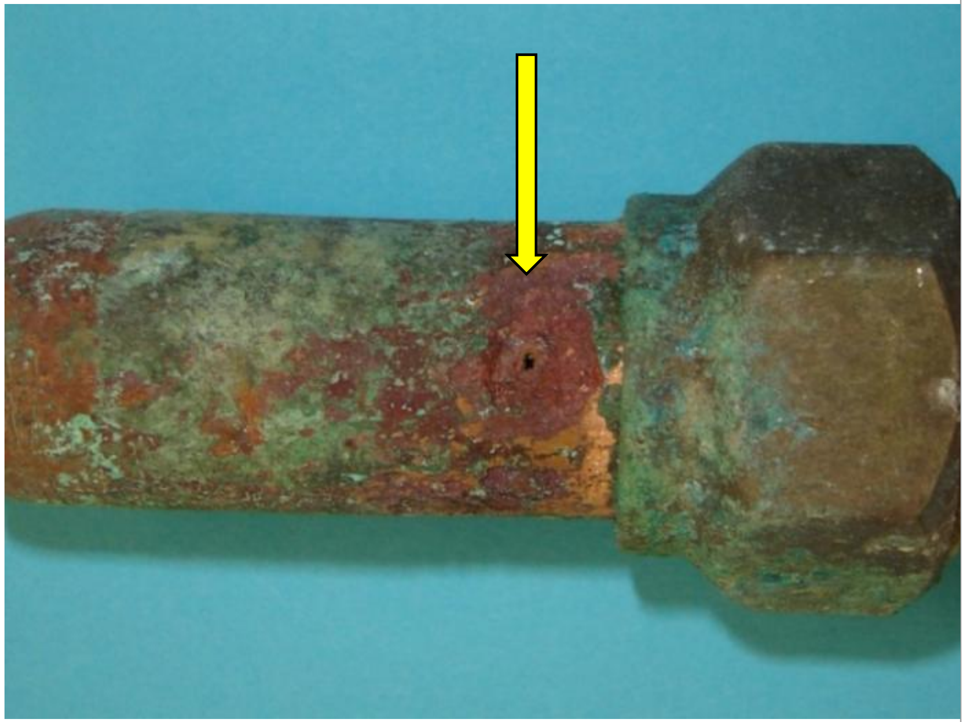


Figure 10: Copper pipe recovered from normal service. Perforation has occurred without structural failure, but the thinned area around the leak indicates that structural failure was a possibility

	
Figure 11: 4" (DN100) cast iron pipe partly blocked by corrosion products. Even if perforated, no or minimal leakage would be expected.	Figure 12: Copper service pipe located after one of the Canterbury earthquakes. The pipe is leaking from a perforation. It is likely that a plug of corrosion product that had been partially or wholly blocking the leak was dislodged by one of the seismic shocks.

Figure 13: Lap welded steel pipe recovered from normal service for condition assessment, illustrating the form of the welded seam.

Figure 14: Large diameter lap welded steel pipe that has failed along the weld in normal service

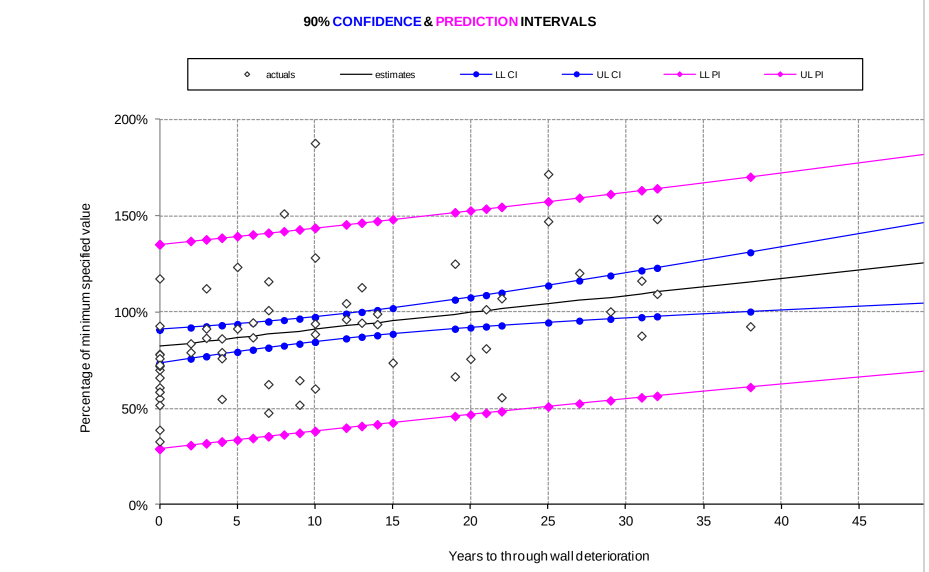
Figure 15: DN100 AC pipe with typical axial split seen in normal service	Figure 16: DN150 AC pipe with wet sandblasting effect. Recovered from normal service.
	
Figure 17: AC pipe with axial split recovered following Canterbury events	Figure 18: AC pipe with wet sandblasting damage recovered following Canterbury events

Figure 19: Fully graphitised cast iron wastewater pipe recovered from normal service. Although the blackened material in the wall is fully graphitised, the pipe remained in service for many years before it was recovered.

Figure 20: AC pipe beam bending failure. This type of failure can occur in pipes that are essentially uncorroded.

Figure 21: Fractured joints in AC pipe from Kaiapoi following one of the Canterbury earthquakes. The relatively short sockets and rigid material are bigger influences than corrosion. Image provided by Iplex Pipelines

Figure 22: Heavily corroded bolt on a gibault fitting. In places the bolts had corroded through completely, but the pipe had remained serviceable, despite experiencing a substantial earthquake approximately 7 years before this image was taken.



CI = confidence interval - used when estimating mean Y for a given X

PI = prediction interval - used when estimating a particular value of Y for a given X

Figure 23: Relationship between observed and predicted time to through-wall deterioration and measured crushing strength as a proportion of the minimum specified strength.

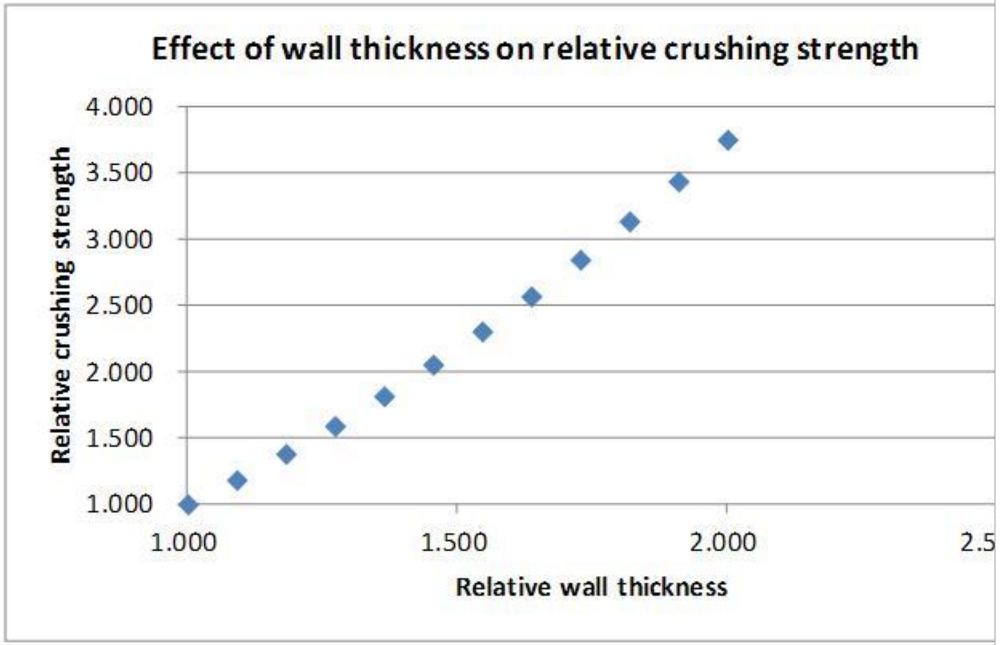


Figure 24: The effect of wall thickness on the crushing strength of an unreinforced pipe sample. Halving the effective wall thickness by corrosion can reduce the crushing strength by almost a factor of 4.

Figure 25: Increased corrosion near the gibault fitting where the coating was damaged while the gibault was installed. The modified fitting is part of the cathodic protection system for the pipeline, which has suppressed subsequent corrosion.