LEVERAGING FAILURE MODES FOR PROACTIVE PLANNING IN ASSET RESILIENCE

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KEYWORDS

Failure modes, contingency planning, asset management, proactive maintenance, water infrastructure.

ABSTRACT

Understanding asset failure mechanisms is fundamental to resilient asset management. This paper demonstrates how failure mode analysis supports proactive planning by linking asset condition, deterioration drivers, and operational constraints to credible failure scenarios and targeted mitigation strategies. Three illustratuve scenarios, representative of situations encountered in practice, are presented: (i) a critical MSCL wastewater pipeline where staged, constructable repair pathways were developed to enable emergency readiness; (ii) application of failure mode analysis to identify operational and maintenance interventions that reduce failure risk; and (iii) management of a critical asset where condition assessment was not feasible, requiring contingency-based asset management planning. The findings highlight improved preparedness, resilience, and decision confidence.

INTRODUCTION

Water utilities are operating in an environment where expectations for reliability continue to rise, while ageing infrastructure, corrosion, changing operating regimes and constrained shutdown windows increasingly challenge traditional approaches to asset management (Australian Infrastructure Audit 2019, 2019; Water Services Association of Australia (WSAA), 2026). For critical water and wastewater mains, a single failure can trigger extended outages, environmental incidents, reputational impacts and high emergency costs (Standards Alert 25 – Supplementary design guideline for sewer pressure mains, 2025) The resilience question is no longer only “which assets are high risk?” but also “are we ready when they fail?”

Many asset management frameworks estimate risk based on Likelihood of Failure (LoF) and Consequence of Failure (CoF). LoF is typically determined based on asset age, generic material categories, historical failure rates and condition assesments (where avaliable – usually limited). CoF typically related to factors such as customer impact, environmental effects, time to repair, and return to service. These methods are useful for portfolio screening, but they can mask localised risks and provide limited guidance for asset-specific intervention and repair preparedness. In practice, this can create a gap between risk assessment outputs and operational readiness: the risk register identifies a critical main, but when failure occurs, repair methods, constructability constraints, shutdown strategy and procurement lead times may still need to be resolved under emergency conditions (Standards Alert 25 – Supplementary design guideline for sewer pressure mains, 2025).

Failure mode and effects approaches provide a practical pathway to bridge this gap by decomposing “failure” into credible mechanisms, each with distinct drivers, indicators and response strategies. In the water sector, failure mode analysis has been used to structure risk assessments and support preventive actions, but it is not always integrated into day-to-day contingency planning and response preparedness (Guoyang Fu, 2021; D Vitanage, 2016; Allen, 2014).

This paper presents an applied approach that uses failure mode analysis to translate technical risk into staged mitigation measures and repair readiness. It combines engineering understanding of pipe materials and operating environments with condition evidence to develop asset-specific risk drivers and practical response pathways.

The remainder of the paper first describes how proactive asset management can be strengthened through failure mode thinking. It then outlines failure mode concepts for common pipeline materials and discusses how these can refine risk scoring. The paper then presents three case studies showing how failure mode analysis can be operationalised through mitigation measures and repair option registers. Finally, the paper discusses how this approach strengthens resilience by reducing downtime and enabling utilities to move from reactive firefighting to strategic readiness.

PROACTIVE ASSET MANAGEMENT AS A RESILIENCE PRACTICE

Proactive asset management is often described in terms of inspection programs and renewal planning; however, resilience requires an additional layer: preparedness for failure events. In practice, proactive management begins with risk screening across relevant assets within each asset class, considering criticality, consequence pathways, and deterioration drivers. The intent is not to treat all ageing assets equally, but to identify the subset where failure would have disproportionate service impacts and where preparedness will materially improve outcomes.

For these assets, proactive planning should focus on reducing uncertainty in three areas. First, utilities need confidence in what is most likely to fail, which requires moving beyond generic material categories and age-based proxies. Second, utilities need clarity on what can realistically be done under emergency constraints, including access, safety requirements, shutdown windows and constructability. Third, utilities must be able to mobilise rapidly, which depends on pre-defined repair methods, procurement planning for long-lead items and pre-approved response arrangements.

Failure mode identification is therefore not only a reliability exercise; it is a readiness tool. It provides the technical foundation to design targeted condition assessments, refine risk scoring using engineering drivers, and prepare repair pathways that align with the most credible mechanisms. This strengthens the alignment between engineering condition assessment and asset management decision-making and supports defensible investment and preparedness strategies consistent with ISO 55000 principles (ISO 55000, 2014).

FAILURE MODE AS THE LINK BETWEEN RISK AND RESPONSE

Failure mode analysis is widely applied in reliability engineering to anticipate how systems may fail and to identify mitigation pathways. When applied to water infrastructure, it provides a structured method to connect asset attributes and exposure conditions to deterioration mechanisms, confirmatory testing, and practical response actions. The key value is not only describing what could go wrong, but identifying what evidence would confirm the mechanism and what repair actions are technically aligned with it.

In reliability engineering, this structured approach is commonly implemented through Failure Modes and Effects Analysis (FMEA), and, where criticality ranking is included, Failure Modes, Effects and Criticality Analysis (FMECA), as outlined in IEC 60812:2018 (IEC60812, 2018). Effective application depends on a fit-for-purpose minimum dataset covering asset attributes and configuration, operating regime (including pressure transients and air management), exposure environment, and available condition/performance evidence.

This approach is particularly relevant for pipelines because failure behaviour differs significantly by material and operating regime. Metallic pipelines may experience localised corrosion pitting and progressive wall loss leading to rupture, while brittle materials are more susceptible to cracking and fracture. Plastic pipelines may experience slow crack growth, deformation under sustained loads (creep), reduction of stiffness over time due to the effects of creep, and fatigue failures due to cyclic loads. Failure mode thinking supports contingency planning that is mechanism-driven rather than generic, improving both response quality and recovery time.

Figures 1 to 5 summarise failure modes for common pipe materials. Importantly, failure modes are not determined by material alone. Installation details, geometry, hydraulic regime and operating conditions can dominate how an asset may fail. For example, metallic pipe wall loss of a trunk water main may be driven by coating defects and corrosion environment, while a sewer rising main can be dominated by air accumulation and H_2S exposure at high points. These drivers highlight why failure mode identification cannot rely solely on age and material categories.

Failure mode analysis provides a pathway to refine risk scoring by incorporating engineering drivers such as pressure regime, transient loading, corrosion environment, air management conditions and known weak points. This supports more defensible prioritisation and improves confidence in decisions on proactive intervention, repair readiness and longer-term renewal planning (AWWA, 2018; 55000, 2014).

DEVELOPMENT OF MITIGATION MEASURES

Failure mode analysis creates value only when it is translated into practical actions. For critical pipelines, mitigation measures must respond directly to credible failure mechanisms and be realistic under operational constraints such as shutdown availability, access limitations, constructability and procurement lead times. This requires integrating condition evidence, engineering judgement and asset management decision-making.

In this paper, mitigation measures are framed as four complementary levers: proactive repairs, operational changes, corrective maintenance and contingency planning. Together they reduce both likelihood and consequence of failure, and improve recovery time when failures occur.

Proactive repairs
Where condition assessment evidence indicates active deterioration or where failure likelihood is increasing, proactive repairs can be implemented to address the most credible failure mechanisms before rupture or service interruption occurs. Examples include localised repair of corrosion hotspots, restoration of coatings/linings, repair or strengthening of joints, and targeted replacement of short sections where defects are concentrated. Proactive repairs are most effective when guided by failure mode assessment outcomes, ensuring that the selected repair method addresses the underlying mechanism rather than only treating symptoms (e.g. leakage). This approach supports efficient capital allocation by focusing intervention on the highest-risk mechanisms and locations.

Operational changes
Operational conditions can be a driver of critical pipeline failure. Failure mode analysis can identify operational contributors such as excessive pressure cycling, pressure transients, abnormal hydraulic conditions, and inadequate air management. Mitigation measures may therefore include operational changes such as optimising pump start/stop regimes, controlling transient pressures, revising operating setpoints, and improving air valve configuration and performance. In some cases, operational changes may provide immediate risk reduction without requiring shutdowns, making them particularly valuable where access or constructability constraints limit near-term repair works.

Maintenance plans
A failure mode-based approach supports the development of maintenance plans that are targeted, measurable, and defensible. Rather than applying uniform maintenance frequencies across an asset class, maintenance activities can be aligned with the degradation mechanisms most likely to affect each asset type and location. This may include scheduled inspection and monitoring, targeted non-destructive testing (e.g. UT thickness validation at critical points), coating condition checks, leak detection programs, and verification of asset appurtenances that influence failure likelihood (e.g. air valves, supports, and thrust restraint systems). Maintenance plans developed in this manner improve confidence in LoF assessment and support early identification of emerging defects.

Contingency planning
For high-consequence assets, contingency planning is a critical component of resilience. Failure mode analysis enables contingency planning to move beyond generic emergency procedures by establishing staged response actions linked to specific failure scenarios. This includes pre-defined repair option registers, constructability verification and procurement planning for long-lead items. Where practical, repair methods can be pre-approved and contractor arrangements established to reduce mobilisation time. This directly improves response speed and reduces downtime.

Overall, the development of mitigation measures based on failure mode assessment provides a structured pathway for utilities to reduce risk proactively and to strengthen readiness for unplanned failures. This approach supports a shift from reactive repair towards strategic asset resilience planning, enabling improved service delivery outcomes and more effective management of ageing infrastructure.

In order to demonstrate the practical application of this idea, three worked examples are provided, which are inspired by real world scenarios. Note that whilst these examples are focused on linear assets, a similar approach can be applied to most other asset classes.

EXAMPLE #1: CRITICAL DN700 MSCL PIPELINE

A critical DN700 mild steel cement lined (MSCL) wastewater pipeline was assessed as being in poor condition with high likelihood of failure. Given its operational criticality and constraints associated with emergency access and repair, a comprehensive failure mode analysis was undertaken to develop a structured readiness framework aligned to credible failure mechanisms.

The assessment considered a range of potential mechanisms including lining/coating deterioration, internal and external corrosion and component-related failures. While some scenarios (e.g. valve-related failures) were assessed as low likelihood based on available evidence, mitigation pathways were still documented to support preparedness for low-probability/high-consequence outcomes.

The primary failure mode was determined to be erosion of the cement lining at the invert due to grit, followed by corrosion of the steel at the lowest point over a critical river crossing in some localised sections only. Whilst the condition assessment determined renewal of the crossing was required, in order to reduce the risk of asset failure at a critical location, repair options were developed in the event of failure at the invert (such as suitably sized welded plates, stainless steel clamps, and a spare pipe piece compatible with the correct size of pipe). In addition, the implementation of suitable maintenance plan was considered, such as additional upstream grit removal in an attempt to remove the source of cement lining damage to ensure other areas do not suffer from the same failure mode. In addition, access to the river banks was organised pre-emptively to ensure response crews could easily access the site in the event of an emergency failure.

A secondary failure mode was identified at the high point under a major highway, just before the discharge maintenance hole. In this case, it was not possible to undertake a condition assessment to understand the condition of this high point due to significant enabling works and permitting required to undertake the activity. Therefore, in order to mitigate the risk of this failure mode occurring, a combination of operational changes, maintenance plans and contingency planning were used. Initially, the air valve was found to be a manual bleed valve – maintenance we able to change this to an automatic air release valve. In addition, chemical dosing of the sewage was investigated to reduce the amount of H_2S production. Thirdly, collaborative discussions were had with the road authority in order to understand upcoming road closures to see if an opportunistic condition assessment could be completed during such events. This would help inform the LoF and timing of renewal.

This case study demonstrates that failure mode analysis can be used to move beyond simply knowing the risk to being genuinely ready for the risk. By converting credible failure mechanisms into staged, pre-defined repair pathways, pre-approved repair methods were established before failure occurred, enabling rapid mobilisation, minimising service disruption, and supporting operational continuity. The outcome highlights the practical and financial benefits of anticipatory planning, showing how failure mode analysis can directly enhance infrastructure resilience, optimise maintenance planning, and strengthen strategic asset management.

EXAMPLE #2: 1900’S CICL TRUNK WATER MAIN

There are a number of critical trunk water main installed in the early 1900s that traverse a high consequence corridor beneath a roadway in a densely occupied area in many major cities in Australia. The main has a known history of failures and is associated with high consequence pathways, including potential impacts to traffic, nearby properties and customer supply. Asset information is incomplete, including uncertainty regarding which sections are cement lined, limiting confidence in deterioration modelling based solely on attributes and age.

Failure mode assessment identified external corrosion and graphitisation as the dominant credible deterioration mechanism. For ageing cast iron assets, these mechanisms can progress non-uniformly and may lead to sudden rupture with limited warning.

In this context, proactive planning focused on strengthening resilience through monitoring and contingency preparedness rather than relying solely on renewal timing. Screening technologies such as acoustic monitoring and leak detection were identified as practical tools to detect emerging leaks and small perforations early, enabling intervention before defects develop into major bursts. The strategy recognises that early detection and repair of small leaks can materially reduce consequence by avoiding high-energy failures and uncontrolled releases.

A contingency plan was therefore prioritised, including pre-approval of traffic management requirements, procurement planning for common repair materials, and development of water supply continuity arrangements. By reducing response uncertainty, the asset owner improves the ability to recover quickly and safely even where the asset remains in service pending renewal planning.

This case study highlights how failure mode analysis supports resilience planning for legacy assets where detailed attribute data is limited: it provides a mechanism-driven basis for monitoring and readiness, enabling utilities to manage risk even when renewal is not immediately feasible.

EXAMPLE #3: SEWAGE TREATMENT PLANT INLET MANIFOLD PIPEWORK

A failure occurred on sewage treatment plant inlet manifold pipework despite the asset being approximately 10 years old. The pipework comprised DN600 DICL and MSCL sections. The early-life failure triggered a failure mode assessment supported by a comprehensive condition assessment including visual inspection, 3D laser scanning survey and wall thickness testing.

The inspection identified inadequate pipe support performance, with 3D scan outputs confirming deflection and sagging along sections of the manifold. These structural conditions were assessed as contributing to settlement and instability over time, and likely influencing hydraulic behaviour by promoting turbulence and increasing the likelihood of H_2S accumulation.

Wall thickness testing identified severe localised wall loss downstream of air valves, including approximately severe wall thickness loss in a DICL section. Air management assessment using the 3D scan outputs confirmed elevation variation along the manifold and identified high points where unvented air pockets could form. These locations aligned with the most severely deteriorated sections, indicating that prolonged air entrapment contributed to crown corrosion driven by H_2S exposure. The evidence suggested that settlement and support deficiencies likely increased air pocket retention and intensified deterioration at critical high points.

Mitigation measures were developed to address both mechanism and operational drivers. These included installation of a new air valve at the identified high point to reduce air pocket retention, corrective works to restore pipe support performance and replacement of the most deteriorated section. Contingency measures were also defined to improve readiness prior to renewal, including flow control strategies to manage surges, investigation of bypass or temporary flow diversion options and procurement of emergency repair materials such as weld-on plates and structural clamps.

This case study demonstrates that failure mode analysis can reveal operational solutions that resilience planning must consider such as air management and support performance.

CONCLUSION

Resilience in water and wastewater infrastructure is increasingly defined by how quickly utilities can recover from failures on critical assets. This paper has shown that failure mode analysis provides a structured pathway to strengthen resilience by translating technical risk into practical readiness. By decomposing failure into credible mechanisms and linking those mechanisms to confirmatory testing and staged repair pathways, utilities can refine risk scoring, target mitigation measures and pre-approve repair options that are feasible under emergency constraints.

Across the three examples, the approach demonstrated benefits for both ageing and young assets: improving repair preparedness for a critical MSCL pipeline, strengthening monitoring and contingency readiness for a legacy cast iron trunk main, and identifying air management and support performance as key deterioration drivers in treatment plant pipework. Failure mode-based contingency planning enables utilities to reduce downtime, minimise disruption and shift from reactive response to strategic readiness. As utilities face increasing service expectations and ageing networks, integrating failure mode analysis into routine asset management practice offers a practical, defensible and scalable method to improve infrastructure resilience.and scalable method to improve infrastructure resilience.

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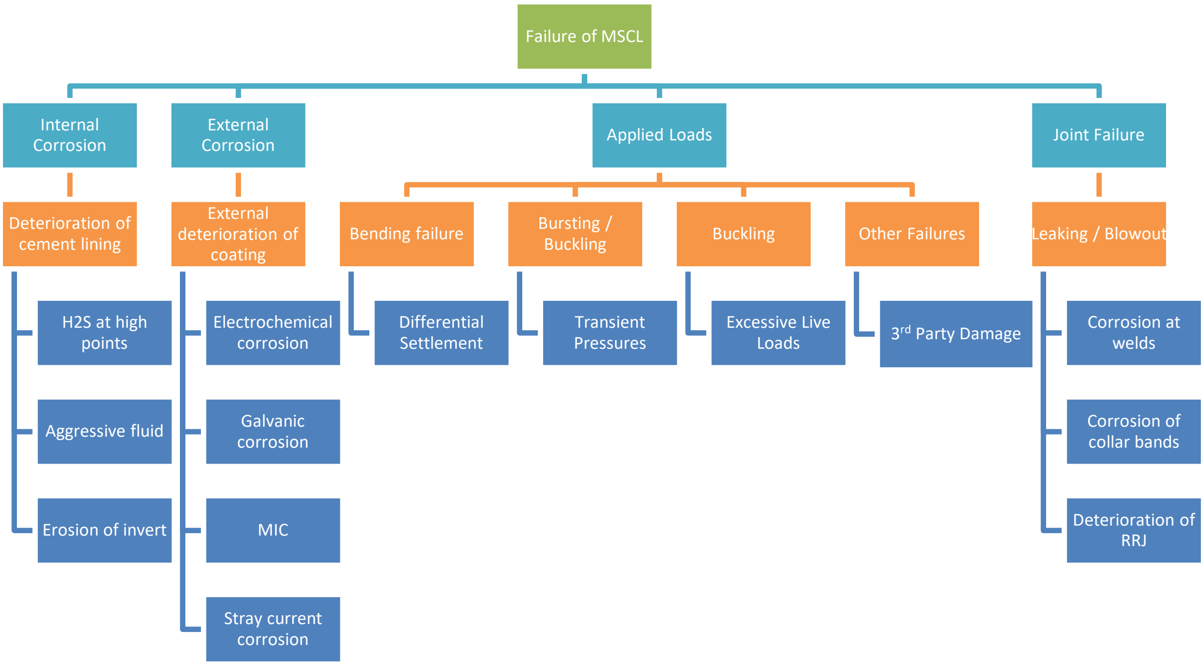

Figure 1: Failure Mode of MSCL Pipes

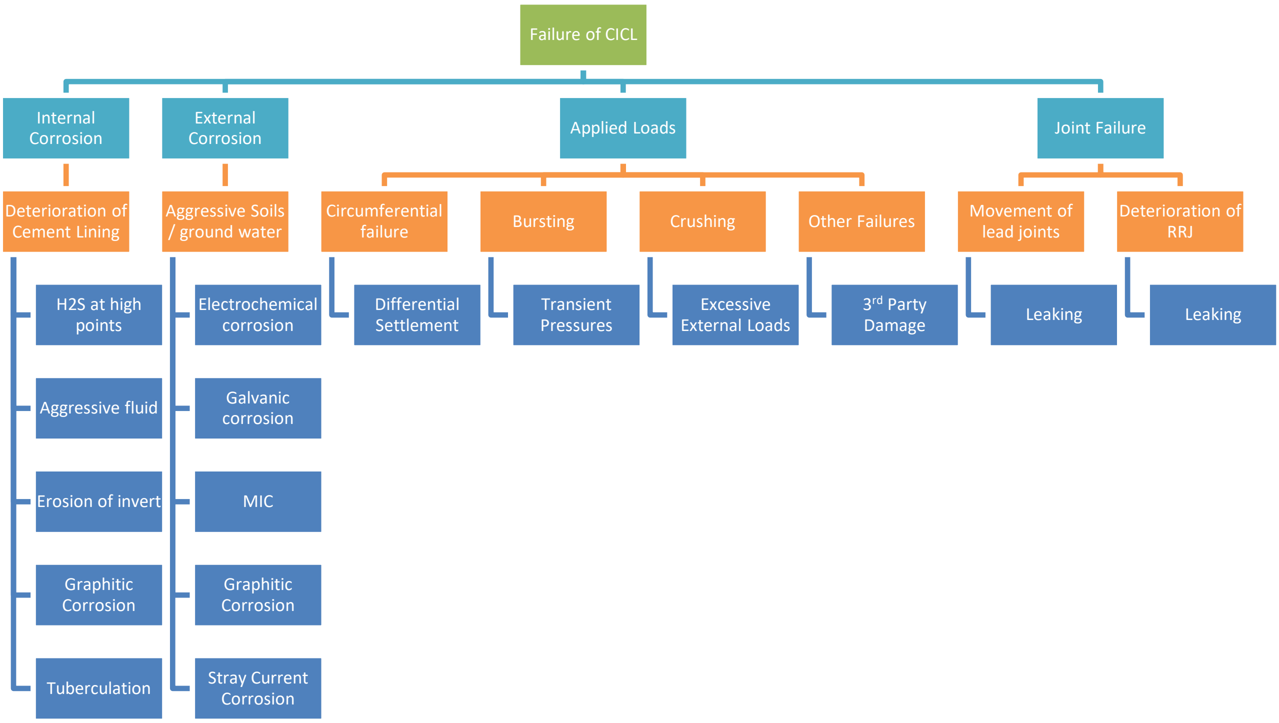

Figure 2: Failure Mode of CICL Pipes

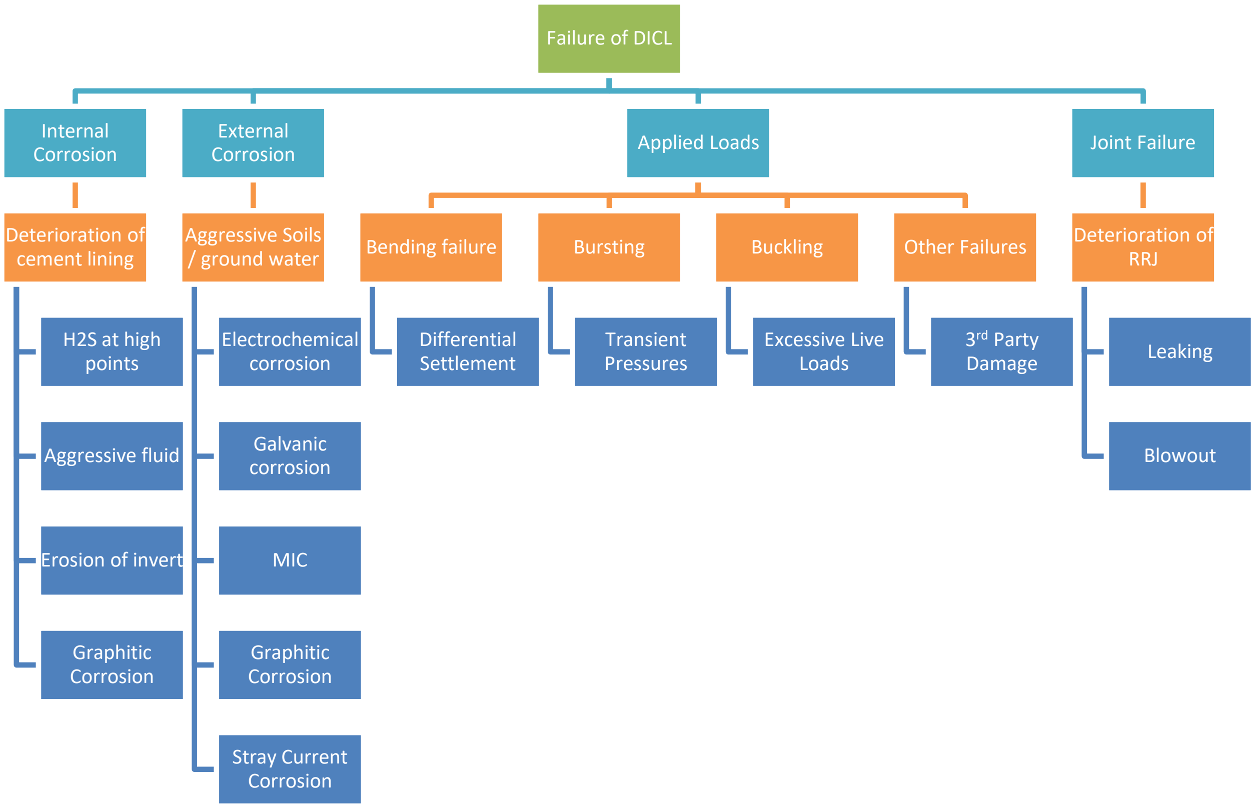

Figure 3: Failure Mode of DICL Pipes

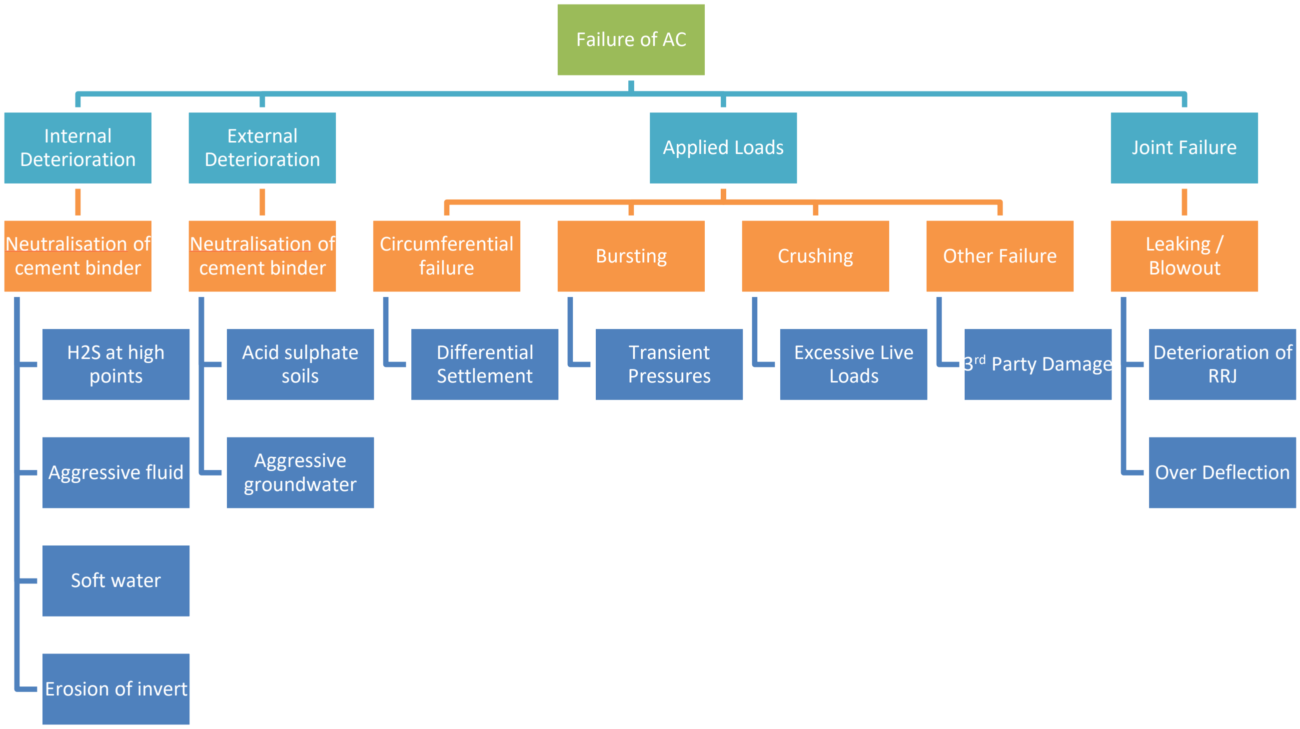

Figure 4: Failure Mode of AC Pipes

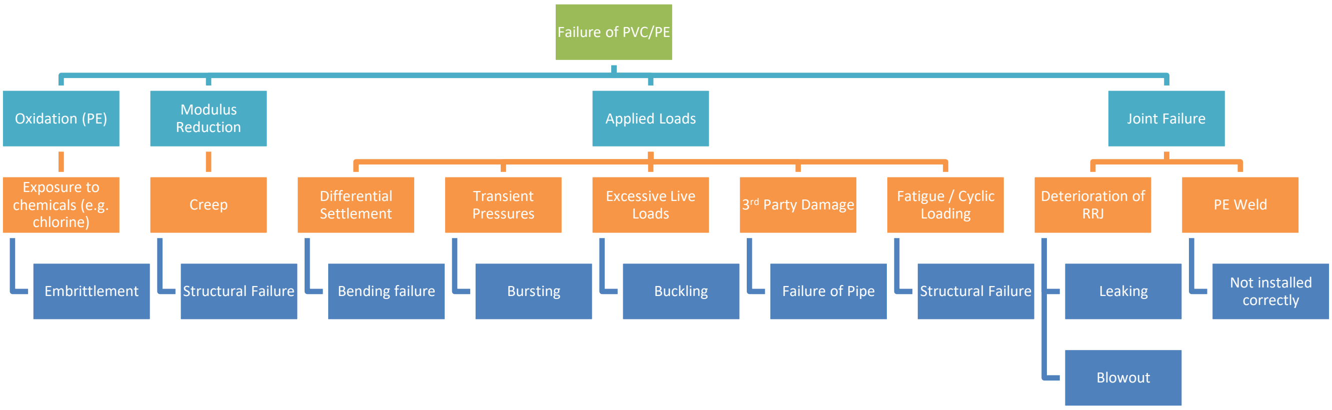

Figure 5: Failure Mode of Plastic Pipes