Reliability of Sewerage Pipelines in South Africa

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Abstract

Water is required for the optimal operation of sewerage pipelines, water treatment and wastewater treatment facilities. In the absence of water, it is impossible to achieve adequate sanitation. The provision of water and sanitation services is acknowledged as a human right for all, both for destitute and affluent individuals. As a developing country, South Africa is experiencing rapid growth in its' number of urban dwellers, and this rapid growth strains sewerage pipelines often leading to clogging, leakage, and deformation. The purpose of this paper is to investigate the factors that affect the reliability of sewerage pipelines and to identify reliability tools that can be employed at different stages of the pipeline lifecycle to enhance reliability. A deductive approach was adopted as the research methodology and a survey questionnaire was employed to obtain the research data from a select engineering population in South Africa, with the test items deduced from a comprehensive literature review. The research population was comprehensive, and snowball sampling was utilized to obtain information. The following reliability tools are mostly utilized by industry in South Africa to improve the reliability of sewerage pipelines, namely fault tree analysis, reliability-based maintenance, failure-mode-and-effect analysis, and hazard and operability studies.

Keywords
Wastewater Treatment, Sewerage Pipelines, and Reliability.

1. Introduction
According to the United Nations (UN) Human Rights Framework, water and sanitation rights have become an explicit requirement with respect to health, development, and a reasonable standard of living (Gupta et al., 2010). In rapidly urbanizing developing regions, urban sanitation coverage has expanded marginally in the recent 20 years, whilst the number of people without access to improved sanitation has increased by 35% (Hawkins et al., 2013). Although urban areas have a higher level of toilet access than rural areas, clean living conditions for destitute individuals are still impacted by access to housing, lack of sanitation, and poor drainage disruptions. Although there has been a decline in the number of urban inhabitants practicing open defecation, this practice has decreased only marginally in Southeast Asia and it has increased in Sub-Saharan Africa (Hawkins et al., 2013).

There are many types of water services, including water supply, sanitation, and the accumulation and treatment of wastewater. Every one of the 58 million individuals living in South Africa utilizes residential water services. However, it is estimated that 7 million individuals lack access to satisfactory water services and 18 million individuals lack satisfactory sanitation services (Department of Water Affairs, 2013). Efficient provision of reliable water and sanitation services are not only fundamental for businesses and industries, but also advance economic development and the elimination of destitution.

The transportation system of water and sewerage pipelines is complex and comprises multiple modes, with each mode having its own complexity that coordinates activities to build system resilience of the communities they support (Mohr, 2015). Economic and industrial prosperity relies heavily on transportation infrastructure such as water and sewer pipelines, roads, and railways (Rizzo, 2010). In developing countries, rapid growth currently occurs in the number of urban dwellers, emanating from transmigration into urban areas from the countryside. This rapid growth crowds the existing transportation infrastructure (water and sewer pipelines) and adds significantly to the multitude of individuals living in the absence of adequate access to basic needs such as clean drinking water and adequate sanitation (Tomar et al., 2008). To meet this ever-increasing demand, sanitation availability, quality, and reliability must advance at a considerably rapid rate and on a much larger scale than in the past (Hawkins et al., 2013).

The objectives of the research are to identify the factors that affect the reliability of sewerage pipelines in South Africa; and secondly, to recommend reliability tools that can be employed at different stages of the pipeline lifecycle to improve its' reliability. Furthermore, the research will provide recommendations on how to enhance reliability of sewer pipelines at different stages of the pipeline lifecycle through the implementation of reliability tools. It is envisaged that the research findings will contribute to the field of knowledge on sewer pipeline failure modes and sewer pipeline reliability in South Africa.

2. Literature Review

In support of the United Nations (UN) Human Rights Framework and the Millennium Development Goals, South Africa established the National Development Plan (NDP) to address the difficulties facing the water and sanitation sector. One of the NDP goals is the provision of inexpensive and dependable access to adequate safe water and sterile sanitation for financial development and prosperity, whilst maintaining a responsible attitude towards the environment (Department of Water and Sanitation, 2018). Even though service delivery has developed well since the country achieved democracy in 1994, the quality of these services remains a challenge. Instability of water supply, blocked and flooding sewers and vandalism, are key issues exacerbating current water supply challenges. Approximately 56% of the 1150 wastewater treatment works (WWTW) and 44% of the 962 water treatment works (WTW) in South Africa are in a critical condition and require urgent refurbishment; whilst 11% of these works are completely dysfunctional (Department of Water and Sanitation, 2018). Pipeline transportation infrastructure contributes significantly to human reform, economic development and long-term viability and forms the foundation and linkage to the economy (Suzuki et al., 2015).

Transportation in pipelines ensures the transit of essential commodities like water, wastewater, and natural gas (Rizzo, 2010). In the long run, sewerage pipeline infrastructure is subject to numerous challenges and risks that arise as it ages and degrades, including third party interference, incorrect operating procedures and inefficient maintenance strategies (Alnoaimi and Rahman, 2019). As a result, failures such as flooding, odour and infiltration can materialize, accompanied by severe repercussions for public safety and health (Akhtar et al., 2014). Inadequate management of assets throughout the life cycle has a detrimental impact on the economy, culture and the environment in the long run (Zhou and Liu, 2015). It is therefore imperative to ensure a sewer pipeline's long-term operational viability and reliability; and that its susceptibilities will survive in crisis situations (Upadhyaya, 2012).

2.1 Factors affecting the Reliability of Sewer Pipelines

Chlebas and Werbińska-Wojciechowska (2016) state that reliability can be defined as a system's capability to perform a specific task at a particular time and under a defined set of conditions, despite the possibility of failing subcomponents. The reliability of equipment, machinery or systems is measured by whether they function satisfactorily as per design requirements under defined conditions and a specified timeframe (Gulati et al., 2010).

The lifecycle framework of sewerage infrastructure projects consists of five phases, namely initiation, planning, design, construction and commissioning, and operation and maintenance (Alnoaimi and Rahman, 2019). The following factors were identified in literature as factors that affect the reliability of sewer pipelines:

Design Parameters: The design parameters are all the internal and external factors that inform the design of pipelines, such as ultimate limit state and serviceability limit state. The ultimate limit state is linked to a single load application or an overload situation; if the limit state is surpassed, the pipeline's structural integrity may be compromised (Bai and Bai, 2014). The serviceability limit state is related to ordinary use circumstances and concerns the structure or structural parts' ability to function (Holicky, 2009).

Environmental Factors: Corrosion is a natural occurrence caused by the pipe's exposure to the surroundings around it. If left uncontrolled, it might potentially compromise a pipeline's structural integrity. Corrosion usually leads to minor leaks in the pipeline (Mahmoodian, 2018).

Fatigue: When the pipeline is improperly maintained fracture or cracking that is stress-induced is likely to occur. Cyclic fatigue is the structural damage caused by fluctuating inner pressures in the pipeline (Mahmoodian, 2018).

Third Party Interference: Third party interference is one of the prevalent causes of deformations in pipelines. When heavy machinery or rocks collide with the pipe, they can cause dents or gouges that alter the line's interior geometry (Mahmoodian, 2018). Third-party interference caused by complicated origins emerges at random and is difficult to predict or manage in advance, posing a severe danger to the safe operation of pipelines (Liang et al., 2012).

Natural Disaster: Natural disasters occur when the natural and technical worlds collide, resulting in the release of hazardous materials, flames, or explosions (Girgin and Krausmann, 2014).

Longitudinal Deflection: Longitudinal deflections occur when pipelines are subjected to permanent ground deformation such as fault movements and landslides (Zheng et al., 2012).

Leakage: Leakage occurs when the depth of the corrosion pit exceeds the thickness of the pipe wall (Mahmoodian, 2018).

Buckling: Local buckling occurs when pipelines are subjected to dynamic loading conditions due to subsurface erosion, earthquakes, and landslides (Han et al., 2012).

Shear Failure: Is the rapid axial propagation of a rupture through a pipeline (Leis and Gray, 2014).

Figure 1 indicates the contributing factors to pipeline failure: welded failures (leakage), corrosion and excavation damage (third party interference) are the largest causes of pipeline failures contributing 34%, 18% and 15% respectively.

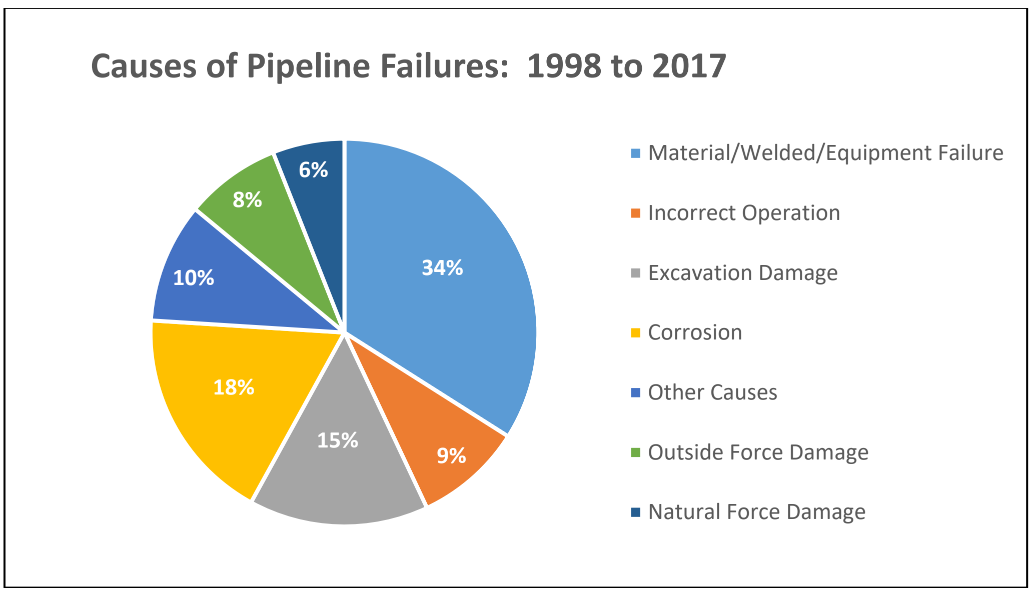

Figure 1. Causes of pipeline failure between 1998 and 2017
(PHMSA, 2018 as cited in Omoya et al., 2019)

2.2 Structural Reliability in Pipelines

Failure of pipelines are characterized by various feasible failure modes, frequently referred to as limit states. Reliability is equivalent to the likelihood that these limit state points of confinement will not be surpassed, and probability densities exist for each variable in the limit state function, indicating their individual statistical properties. Structural reliability analysis can be used for the following purposes (Mahmoodian, 2018):

- To forecast the performance of pipelines and how funding can be distributed to the most critical components;
- As a study to determine how repair, maintenance, and rehabilitation will affect the lifespan of pipelines; and
- To analyze the feasibility of different design options and their effect on the operational life.

2.3 Reliability Methods

The following reliability tools or methodologies were identified from literature to increase the reliability of sewer pipelines when applied at different stages of the sewer pipeline lifecycle:

Hazard and Operability Study (HAZOP): HAZOP studies identify the areas where deviations can occur in the project or designs' scope and objectives (Baybutt, 2015). The application of HAZOP has increased over time to other facilities due to its' ability to identify hazards and operational issues as well (Dunjó et al., 2010).

Fault Tree Analysis (FTA): FTA translates a physical system into a logical diagram, making it one of the most widely used approaches in industry for reliability and safety calculations (Baig et al., 2013). FTA can be utilized as both a diagnostic tool forecasting the most likely system failure, and as a design tool to identify accidents (Sharma and Singh, 2015).

Failure Mode and Effect Analysis (FMEA): FMEA is a widely used tool in the design of industrial processes for examining failure mechanisms and reducing the effects of related failures. Therefore, it assists in identifying actions required to enhance the product and processes (Xiao et al., 2011).

Reliability Based Maintenance (RBM): Maintenance is defined as all technical and management measures taken during a product's or asset's usage term to maintain or restore the product's or asset's required functioning (Shin and Jun, 2015).

Failure Reporting, Analysis and Corrective Action System (FRACAS): FRACAS is centred on the systematic reporting and analysis of failures that occur during the manufacturing, inspection, testing, and operation phases (Lee, Chan and Jang, 2010). If used correctly, FRACAS is a good reliability tool for ensuring asset and process improvement by eliminating failure (Biswas, 2016).

Quantitative Risk Assessment (QRA): QRA is a tool that can deal with a wide range of hazards based on defined scenarios. Although quantitative risk assessment is efficient in predicting accident probabilities and consequences, it does not explicitly address accident root causes or other crucial elements that might contribute to major accidents (Chen et al., 2017).

Physics of Failure (PoF): PoF is a method of developing reliable products that avoid failure by using knowledge of the core causes thereof. It is based on failure reliability technology, which investigates regularities of failure based on product failure causes and mechanisms (Sadiku et al., 2016).

Design of Experiments (DoE): According to Antony, Coleman, Montgomery, Anderson and Silvestrini (2011), DoE allows for the simultaneous and efficient investigation of the effects of numerous systems or process factors, resulting in a better understanding of the system.

3. Methods

This research employed a quantitative approach and used it to collect primary data. Quantitative methods yield outcomes that are simple to summarize, compare, and generalize (Kabir, 2016). The deductive approach was employed in this research: Park et al. (2020) state that the deductive research approach and quantitative data analysis are mostly used in the positivist research paradigm. The research instrument employed was a survey in the form of a questionnaire to determine the application of reliability tools for improving the reliability of sewerage pipelines. In-depth questions were utilized to gather data which allowed a comprehensive understanding of, and response to, the research questions. The questionnaire survey tested the application of engineering reliability tools in industry for increased sewer pipeline reliability.

4. Data Collection

A key goal of the data collection process is to gather data of high quality that will be analyzed to construct logical and comprehensive responses to research questions (Kabir, 2016). The current research's population of interest is comprehensive and required the solicitation of information from a population that was difficult to reach (Shaghaghi et al., 2011). The snowball sampling methodology was identified as the best method for this research based on literature that suggests that snowball sampling is often employed when a difficult to reach population is to be studied (Kirchherr and Charles, 2018). The data collection took three months, and a structured survey questionnaire was used to collect data. The prospective participants (engineers and technicians) were engaged and requested to participate in the survey and to extend the survey to other subject matter experts within their network. A total of 68 participants responded.

5. Results and Discussion

The research findings are presented and discussed as follows through six sections: Section 5.1 presents the demographic profile of the participants and their general understanding of sewer pipeline and reliability; Section 5.2 discusses factors affecting the reliability of sewer pipelines; Section 5.3 outlines the participants' understanding of reliability tools regarding sewer pipelines; Section 5.4 presents the application of reliability tools at different stages of the sewer pipeline lifecycle; Section 5.5 presents the proposed improvements and the discussion concludes with Section 5.6 which details the validation process for the research.

5.1 Demographic Profile and Organizational Context

The demographic profile of the participants and their organizational context are presented in Table 1 and their organization context in Figure 2. The demographic profile presents the participant's tenure and engineering discipline within an organization, and organizational context discusses the experience of the company in sewerage pipeline infrastructure and maintenance.

Table 1. Demographic profile

Item	**Frequency**	**Percentage**
How long have you been working in the industry?		
Less than 1 year	0	0%
2 – 5 years	5	7%
6 – 10 years	16	24%
11 – 15 years	11	16%
16 – 20 years	14	21%
More than 20 years	22	32%
Total	**68**	**100%**
Which discipline (s) do you fall under?		
Project Management	0	0%
Systems Engineering	1	1%
Project Engineering	6	9%
Mechanical Engineering	5	7%
Civil Engineering	19	28%

Item	**Frequency**	**Percentage**
Facilities Management	2	3%
Technical Management	10	15%
Reliability Engineering/ Management	11	16%
Maintenance Engineering/Management	14	21%
Other (Specify)	0	0
Total	**68**	**100%**

The participants were asked to specify their years of experience in the industry and the function or discipline which they fall under with the aim of determining the sample features. The majority (32%) of participants have over 20 years' work experience and participants with fewer than 5 years' work experience constitute the minority group (7%). This indicates that most participants have sufficient and significant experience to understand and interpret the survey questionnaire and provide valuable input. The function/discipline status indicates that Civil Engineering comprises the majority (28%) of participants, with 21% in Maintenance Management/Engineering and the minority (1%) in Systems Engineering.

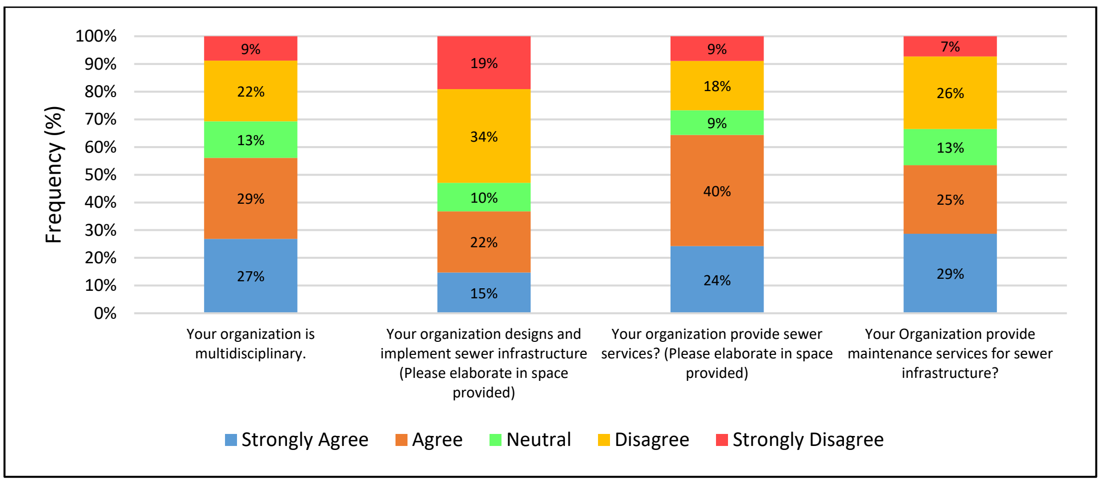

Figure 2. Organizational Context

In this section participants were requested to select the most applicable answer to best express their views ranging from strongly agree (1), agree (2), neutral (3) disagree (4) to strongly disagree (5). The results are depicted in Figure 2. The difference between strongly agree and agree is not significant as both ranges express the same perception; similarly for strongly disagree and agree. Therefore, for the analysis of the current research, the data for strongly agree/ agree and strongly disagree/disagree will be merged. The majority (Strongly agree and agree = 56%) of the participants indicated that their organization is multi-disciplinary, 13% reserved their comment and 31% indicated that their organization is not multi-disciplinary. The majority (Strongly disagree and disagree = 53%) of the participants maintained that their organizations do not design and implement sewer infrastructure, rather external consultants are contracted to do so. Their organizations do, however, play a vital role in providing the operational service subsequent to commissioning and handover. Hence, 64% and 54% of the participants agreed that their organizations provide sewer services and maintain sewer infrastructure, respectively. Some of the participants that disagreed with the former and the latter further elaborated and specified that their organizations play a role of sector leader and are responsible for policy development, regulation, monitoring.

5.2 Factors that affect the Reliability of Sewer Pipelines

The literature review presented nine factors that affect the reliability of sewer pipelines, namely design parameters, environmental factors (corrosion), fatigue, third party interference, natural disasters, longitudinal deflection, leakage, buckling and shear failure. These factors were tested in industry and based on the results the highest contributing factors were design parameters, environmental factors (corrosion), fatigue, third party interference, buckling and leaking.

Figure 3 indicates that 72% (26% strongly agree and 46% agree) of the participants agreed that poorly defined design parameters is the factor that most compromises the reliability of sewerage pipelines; and can lead to poor, incorrect and inefficient maintenance strategies. Structural failure, exhaustion or excessive deformation of the structure may result. 21% of the participants disagreed and 7% reserved their comments.

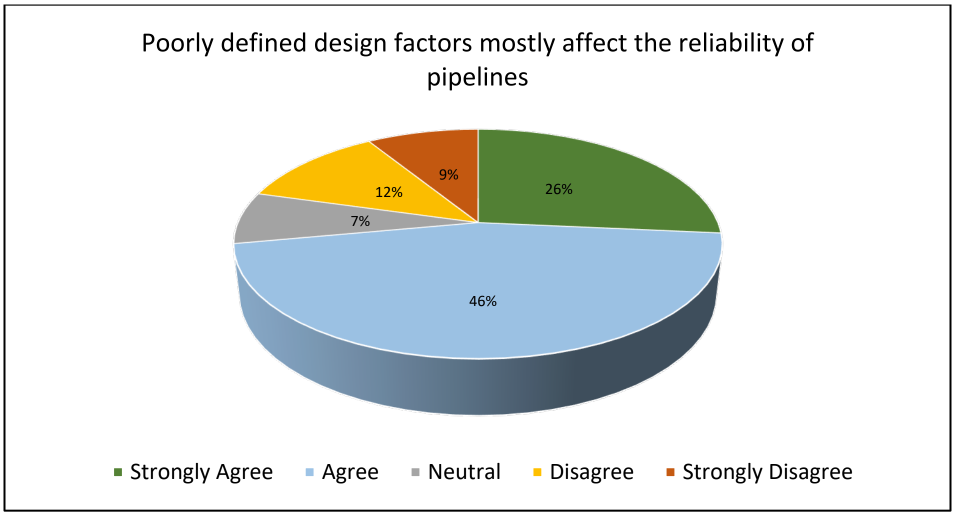

Figure 3. Design Parameters

5.3 Reliability tools in relation to Sewer Pipelines

The majority 55% of participants believed that FTA determines the root cause of failure and is most effective when employed in the design stage of the sewerage pipeline lifecycle. Hence 58% of the participants disagreed that FTA is a reliability tool that can be used in both operations and maintenance. According to Sharma and Singh (2015), FTA can be utilized as a design tool to identify and prevent accidents. The research focussed on eight reliability tools as presented in section 2.3 and these were tested in industry. Four tools or methodologies emerged as the most implemented or utilized in South African industry, namely HAZOP, FTA, FMEA and RBM. However, according to Antony et al., (2011), there have not been as many attempts to improve non-manufacturing processes using powerful quality and reliability improvement approaches as the application of DoE (Figure 4).

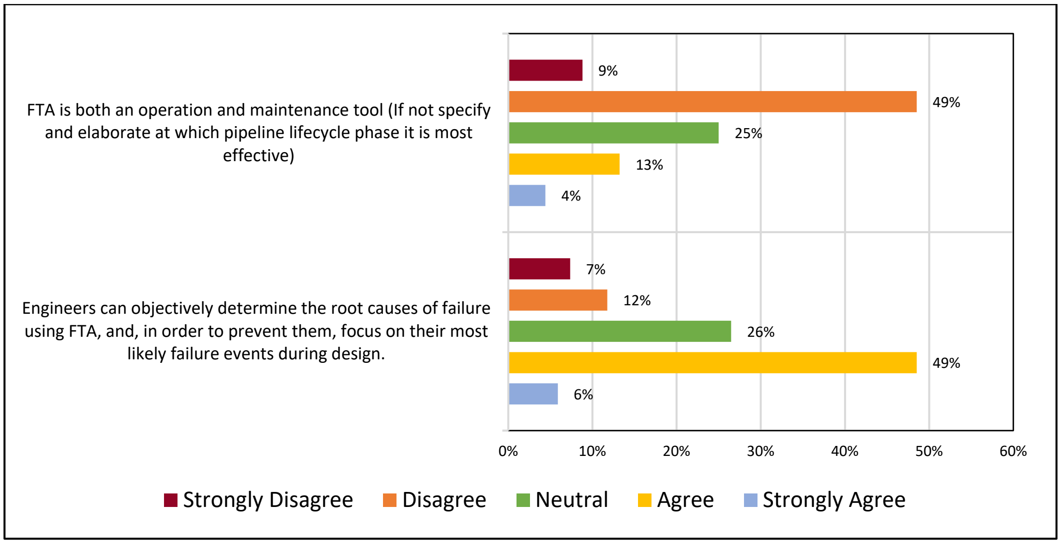

Figure 4. Fault Tree Analysis

5.4 Application of Reliability Tools in different stages of the Sewer Pipeline Lifecycle

Table 2 indicates that only HAZOP is employed in the initiation phase of the sewer pipeline lifecycle as a reliability improvement tool. In the planning phase, HAZOP and QRA can be employed to determine the potential hazards that each option or solution will pose and to identify the potential risks of each defined scenario. This analysis allows selection of the most feasible solution considering the potential hazards and risks of each option. The respondents indicated that six tools, namely HAZOP, FTA, FMEA, QRA, PoE and DoE, are used in the design phase of the sewer pipeline lifecycle. Correct application of these tools promotes an optimized sewer pipeline design by taking a deep dive into the detrimental surroundings factors during construction, commissioning and operation that can transpire. These may include potential risks, hazards, probable technical failures, errors, and accidents. FMEA is a widely used tool in the design of industrial processes for examining failure mechanisms and reducing the effects of related failures (Xiao et al., 2011).

In the construction and commissioning phase, the respondents indicated that FRACAS and PoE can be employed to yield optimum results. Incorrect implementation of the constructability plan, installation and commissioning procedures will negatively impact the short and long-term reliability of the sewer pipeline. Poor quality control measures and ineffective pipeline pressure testing methods can change the microstructure of the pipeline and fail to detect leakages. The FRACAS approach can be used to gain in-depth insight into the historical unexpected behaviour of sewer pipelines (with similar specifications and structural characteristics) during commissioning and thus create scenarios for shortcomings and take necessary steps to prevent them from re-occurring. PoE can be applied to optimize the constructability plan by providing information on why and when pipeline components fail during construction. In addition, implementation of HAZOP, FTA, FMEA, RBM, FRACAS, and POE in operation and maintenance will enhance the reliability of the sewer pipeline and thus extend its longevity. Information and data (potential hazards, technical failures, operational probable errors and accidents) obtained through the application of HAZOP, FTA, FMEA and FRACAS can be utilised to effectively implement RBM in line with Standard Operating Procedures thus preventing unplanned breakdowns, failures and accidents from materializing.

Table 2. Reliability tools/methods at different stages of the sewer pipeline lifecycle

Reliability Tool	Initiation	Planning	Design	Construction/ Commissioning	Operation/ Maintenance
Hazard and Operability (HAZOP)	Vital	Vital	Vital		Vital
Fault Tree Analysis (FTA)			Vital		
Failure Mode and Effect Analysis (FMEA)			Vital		Vital
Reliability Based Maintenance (RBM)					Vital
Failure Reporting, Analysis and Corrective Action System (FRACAS)				Vital	Vital
Quantitative Risk Assessment (QRA)		Vital	Vital		
Physics of Failure (PoF)			Vital	Vital	Vital
Design of Experiment (DoE)			Vital		

5.5 Proposed Improvements

According to Upadhyaya (2012) it is imperative to ensure a system's long-term viability and reliability, to ascertain that it is operational and that its susceptibilities will survive in crisis situations. The results indicate that most participants believe it is imperative for organizations to keep abreast of the latest reliability and maintenance strategies; with select participants suggesting that information produced by their organization is not essential to understand the root cause of pipeline failure. This may suggest that select organizations do not invest in knowledge management platforms and historical data collection systems and that the information they store is to a certain extent redundant and has minimal efficacy in relation to pipeline reliability. Knowledge management platforms and historical data collection systems are crucial in current and probable failure analysis; and implementation of reliability tools in the absence of these systems will yield ineffective results. Therefore, organizations that design, operate, manage, and maintain sewer pipelines should focus more on knowledge management initiatives to gain deeper insight in the root causes of each factor that affect sewer pipeline reliability, and prioritize each root cause in order of consequence. In addition, prime focus should be on investing in continuous data collection systems via Internet of Things (IoT), the use of historical sewer pipeline data (to understand trends and similarities), and employee skills development in the following reliability tools and their application; FTA, FMEA, HAZOP and RBM.

5.6 Validation

Drost (2011) defines validity as the ability of a measure to accurately reflect its purpose. For instance, an alarm clock that rings at 6:00am when it is set to go off at 5:30am is invalid, as it is not ringing at the desired time (Heale and Twycross, 2015). The current research focused on content validity which involves the appraisal of a new survey instrument to ascertain that it incorporates all the required research items and excludes those that do not define a certain construct (Taherdoost, 2016). Thus, content validity was primarily concerned with how well the survey questionnaire elicited and tested the desired information.

The most widely used internal consistency metric is Cronbach's alpha (Hajjar, 2018). The current research employed Cronbach's alpha using SPSS to test the reliability of the research instrument. According to Hajjar (2018) alpha coefficient ranges from 0 to 1, an alpha value of 1 is the highest, indicating full internal consistency. Anything below 0.7 is regarded as inconsistent and unreliable. The current research opted for an alpha coefficient threshold of 0.7 for reliability and consistency.

6. Conclusion

The research investigated the factors that affect the reliability of sewerage pipelines in South Africa, and identified and recommended reliability tools that can be employed at different stages of the pipeline lifecycle to enhance the reliability of the pipeline. The respondents suggest that design parameters, environmental factors (corrosion), fatigue, third party interference, buckling and leakage affect the reliability of sewer pipelines mostly. In general, welded failures result in leakages. The literature data in Figure 1 (Literature Review) is congruent to the current research results, the data in Figure 1 indicate that welded failures (leakage), corrosion and excavation damage (third party interference) are the largest causes of pipeline failures each contributing 34%, 18% and 15% respectively. Hence, the industry results reflect and support the findings from literature from a South African perspective.

According to the research findings, four reliability tools emerged as the most implemented or utilized in the industry, namely HAZOP, FTA, FMEA and RBM. As such, more focus on these reliability tools will yield the most favorable results in improving the reliability of sewerage pipelines, provided that implementation takes place at the correct stage of the sewer pipeline lifecycle.

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