Classification of Water Pipeline Failure Consequence Index in High-Risk Zones: A Study of South African Dolomitic Land

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Abstract. Increasing numbers of pipeline breakdown experienced by utilities undoubtedly raise alarms concerning the anticipated failure consequences. Seemingly mild, these consequences can however, fluctuate to severe or fatal, especially in high risk locations. Utility personnel are therefore pressured to employ up-to-par operational policies in attempt to minimize possible fatalities. This however, may be overwhelming considering inherent uncertainties that make it difficult to understand and adapt these consequences into utilities' risk management structure. One way of handling such uncertainties is through the use of Bayesian Networks (BNs), which can comfortably combine supplementary information and knowledge. In this paper therefore, we present an overview of the causes and impacts of pipeline failure. We aggregate and classify failure consequences in a select high risk zone into four indexes; and finally, we outline how BNs can accommodate these indexes for pipeline failure prediction modeling. These indexes function as effective surrogate inputs where data is unavailable.

Keywords: Pipeline failure · Failure impacts · Consequence index · Dolomitic land · Predictive modeling · High-risk zones · Water leakage

1 Introduction

Pipeline systems are a fundamental division of the social infrastructure, considering their facilitation of material conveyance, supply and distribution to and from various locations [1]. With such a worthy responsibility, they are under constant performance and operational pressure [2], which in one way or another destabilizes their structural orientation leading to failure [2, 3]. Failures along pipelines transpire in different ways, and therefore have attracted an extended scope of definitions, largely based on suitability. In [4–7], failure is defined as the occurrence of bursts along a pipe or several other pipes in a network, while other research outputs [3, 8, 9] describe pipe breaks as a form of failure. In [10], cracks along the pipelines qualify them as failure candidates whereas in [11], an eventual pipe collapse due to continued exposure to several pipe deteriorative aspects is defined as failure. Regardless of the diversity in manifestation,

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failure results to one uniform consequence (material loss). Therefore, *pipeline failure* can generally be defined as 'the unintended loss of pipeline contents' [12].

These failures are unavoidable [2], just as much as their unanticipated results are undesirable [2, 13–15]. For this reason, utilities are constantly on the lookout for better management and preventive tools in attempt to minimize extensive losses [2, 13, 16]. In oil and gas facilities, pipeline failures are undoubtedly hazardous and fatal [13] However, an almost equal level of fatalities should be expected in the case of water pipeline failure, because they are accompanied with exceedingly widespread impact index [2].

2 Causes of Water Pipe Failures

There exists a significant body of literature analyzing various aspects that directly or indirectly influence pipeline breakdown, for instance, in [2] factors causing failure in Pre-stressed Concrete Cylinder pipes (PCCP) and metallic pipes were examined. In both materials, corrosion was established as the highest failure contributor. An almost similar review conducted on waste water pipes indicated that construction dynamics and local external influence, as well as pipe age and other pipe characteristics and also contributed to failure [11]. In yet another study [17], pipe material, inappropriate pipe operation, earth movements and weather fluctuations were identified as possible threats on pipe integrity. To add to the list, improper pipe installation and water hammer surges were identified as possible failure threats in [9].

Identification of the factors influencing failure may be extracted with ease from the abovementioned articles [2, 9, 11, 17]; however, understanding how the different factors individually contribute to failure is of equal importance. An extensive research on corrosion effect was conducted in [9, 18, 19]. The respective studies adequately explained how corrosion affects failure in different pipe materials. Effects of pipe age on failure was also discussed in [3, 4, 8, 9, 18, 20], with [4, 9] also reporting on how pipe material influences failure. An aspect reported to highly test the strength of a pipe material however, was environmental fluctuations, especially temperature, given its ability to catalyze reactions, leading failure [9, 21]. Due to space limitations, a summary of influential factors, which in one way or another, contribute to pipeline failure, together with their possible nature of effect is given in Table 1.

Table 1. Summary of pipeline failure causes

Category	Individual factors	Mode of influence
Environmental factors	Corrosion	Causes loss of pipe mass through oxidation to soluble iron
	Ground movement	– Causes permanent ground damage – Affects pipe layout hence leads to breakages – Causes soil movement
	External load	– Increases the external stress level of the pipes – Exists in form of roads, railways, buildings, tunnels, excess soil, mud, dust, glaciers or frost

(*continued*)

Table 1. (*continued*)

<table>
<tr><th>Category</th><th colspan="2">Individual factors</th><th>Mode of influence</th></tr>
<tr><td rowspan="3"></td><td colspan="2">Temperature fluctuations</td><td>– Extremely cold temperature causes freezing, and at freezing point, water begins to expand forcing pipes to swell and break
– High temperatures catalyses chemical reaction in water, hence propagating corrosion</td></tr>
<tr><td colspan="2">Soil acidity or alkalinity</td><td>Influences chemical reaction externally thereby propagating external corrosion</td></tr>
<tr><td colspan="2">Soil moisture content</td><td>Freezing of soil moisture content causes expansion of the soil hence creates vertical forces on pipes</td></tr>
<tr><td rowspan="5">Pipe properties</td><td rowspan="3">Static factors</td><td>Material</td><td>Depict pipe strength characteristics and also determines pipes corrosion characteristics</td></tr>
<tr><td>Pipe joints</td><td>Are affected by external pressure and earth movements, hence prone to leakages</td></tr>
<tr><td>Diameter</td><td>Small diameter pipes are identified to be more prone to failure than large diameter pipes</td></tr>
<tr><td rowspan="2">Time dependent</td><td>Age</td><td>Indicates the length of time a pipe has been exposed to loading and the surrounding environment</td></tr>
<tr><td>Break history</td><td>Clearly states the condition of a particular pipe, the more the breaks the poorer the condition</td></tr>
<tr><td rowspan="4">Poor installation/poor workmanship</td><td colspan="2">Pipe embedment</td><td>Poor bedding deprives adequate support to the pipe leading to joint movements. Lack of uniformed bedding offers poor support</td></tr>
<tr><td colspan="2">Improper alignment</td><td>Causes longitudinal breaks in pipes, because of improper pipe gradient</td></tr>
<tr><td colspan="2">Poor backfilling</td><td>– Failure to remove rocks and trees from trenches or supporting pipe sockets on displaceable bricks or blocks leads to pipe breakage
– Leaving decomposable materials can catalyze chemical decay and corrosion</td></tr>
<tr><td colspan="2">Damage due to improper handling</td><td>Poor handling of pipe during installation or manufacturing may result in cracks or other physical deformities</td></tr>
<tr><td>Manufacturing defects</td><td colspan="3">Manufacturing defects are the largest contributors to pipes initial failures. Pipes should be carefully tested for cracks or any other possible defects before they are put to use, for instance, Cast Iron (CI) pipes should undergo “ring testing” after manufacturing and before installation to ensure its safety</td></tr>
</table>

3 Consequences of Pipeline Failures

The impacts of pipeline failures, as described in [13] refer to the quantification of risk, which could be in the form of the number of affected individuals, damaged property, polluted environment, delayed missions and amount of product lost. These impacts materialize in different ways, directly and indirectly, and for this reason, there is a wide range of literature focusing on different failure consequences [2, 13, 16]. In [16], the financial impact of pipeline failure was analyzed and classified into three major categories: (i) value of product possibly lost, (ii) value of property damage (private, public and operator property) and (iii) the cost of recovery and cleanup.

Correspondingly, in [2], cost implications of failure were again studied and classified into direct, indirect and social costs. As one of the most critical social costs however, poor water quality resulting from contamination due to intrusion of particles into the pipe as a result of pressure reduction was also discussed. Among other effects of contamination, possible poisoning, illnesses as well as death of persons were identified. Similarly, another classification was done in [13], and failure consequences were organized into three general categories given as: (i) personnel, (ii) environmental and (ii) economic consequences.

Apart from the already identified consequences of pipeline failures, it was made clear in [2] that extensive research is still required so as to assist in the determination of the true magnitude of the indirect and the social consequences of pipeline failures. This would consequently enhance inclusion of these impacts in rehabilitation modeling. However, determination and quantification of some specific losses may be difficult, and utilities too may consider their information as confidential [2, 13]. It is important therefore, to classify some of these consequences in a way that makes them easily adaptable in the development of failure prediction models. This may as well accommodate the incorporation of non monetary consequences in modeling pipeline failure for extended decision making.

4 Failure in High Risk Zones

High risk zones in this context refer to areas that are underlain with naturally occurring or man-made grounds that are potentially challenging, and are commonly associated with structural damage [23]. Classification of a region as a high risk zone is however relative, given the severity of risk or consequences it may suffer from failure or by the different ways it is likely to contribute to failure. In a detailed report relayed in [23], potentially unsafe grounds were categorized into four categories; (i) expansive, (ii) collapsible, (iii) dispersive soils, as well as (iv) soft clays. Expansive soils were identified as those that have the potential to expand or shrink depending on variations in soil moisture conditions [9, 23]. Collapsible grounds were described as those that are likely to undergo abrupt volume reduction in the presence of sufficient triggering mechanisms. Soft clays and dispersive grounds, however, were said to be associated with extreme moisture contents and large volumes of Exchangeable Sodium Percentage (ESP) respectively [23, 37]. For an in-depth understanding of the problematic soils and the different mechanisms leading to hazardous events, a comprehensive review is done in [23, 37].

4.1 The Study Area

Situated in Gauteng, South Africa, Doringkloof region is a complete Dolomitic land. Dolomitic or dolomite land refers to regions underlain by dolomite rock, either directly or at shallow depths of possibly below 100 m [24, 26, 37]. The rocks are composed of a carbonate of magnesium and calcium; and are soluble in water [24, 25]. When these rocks dissolve in water, voids and cavities are created within the rocks, the upper soil cover may then collapse in to fill the void causing massive ground movement [24, 26, 37]. This qualifies the region to be categorized under collapsible soil [23]. Public works reports [25] as well as other research findings in [24, 26, 27] indicate that approximately 38 lives have been lost due to sinkhole formation in various regions including homes, entertainment and business premises. Sinkholes result from the collapse of surface soil into the hollowing underground rocks created as a result of rock solubility leading to formation of voids and cavities [24–26, 37].

An illustration of the process of sinkhole formation is shown in Fig. 1. Apart from the naturally occurring conducive underground activities; human activities also propagate the formation of sinkholes [25]. They may occur soon after installation of infrastructure due to poor workmanship or after some time due to material deterioration, which in this case, one major contributor is leakage from wet services like clean and waste water mains [25]. For this reason water leakage in such a risky environment should be treated with utmost urgency, and as much as possible, proactive measures should be put to place in attempt to capture failure possibilities before actual occurrence.

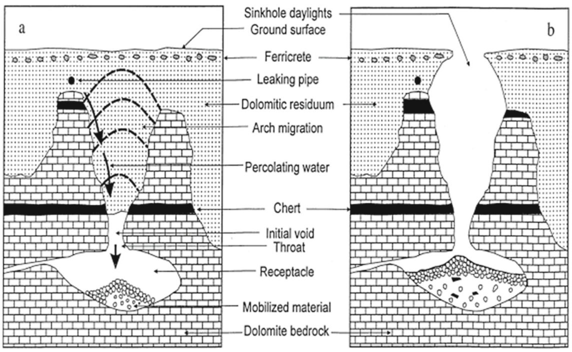

Fig. 1. Sinkhole formation mechanism [26]

5 Classification of Failure Consequence Index

The potential implication of failure in a given pipe section stands out as the most significant factor for the determination of the intensity and kind of effort that ought to be invested into collecting data about the water main [2]. In addition, it determines the level of prioritization of the water main for rehabilitation, repair or replacement [2, 22, 30]. For this reason, estimation of impending consequences from a pipe failure ought to address the questions: “What can be harmed by the failure? And how badly are they likely to be harmed?” [12]. Response to these questions consequently makes it possible to determine the water mains that have the most potentially severe outcomes in the event of failure, making it possible to exercise prioritization [22]. In addition, inclusion of the factors that addresses the said concerns in failure modeling would support the development of rehabilitation, replacement or condition assessment tools and programs using available limited resources [22, 30].

Following a rather satisfactory investigation, it was pointed out in [30] that apart from the general effects resulting from pipe failure, influential factors for failure modeling ought to address specific characteristics. These aspects include land use around the water main, population that might possibly be affected by the failure, the length and diameter of the water main. In a subsequent analysis conducted in [30] therefore, the consequences of pipeline failure were rated using three matrices given as: Land Use (LU), Pipe Diameter (PD) and the Population density (PP). Among all the classified consequences, pipe diameter was considered to hold the highest impact on the consequence level. This is largely due to the fact that pipe diameter dictates whether the pipe is a trunk main or an ordinary distribution main, which in turn quantifies the amount of loss that may be accumulated from a failure [2, 22, 30].

In yet another investigation, a model was developed in [5] to assist in determination of the risk of burst in trunk water mains. During the development of the consequence element of the model, the quantification was estimated by mainly considering repair and replacement costs and the costs of damage to private and commercial property. Other factors included were sensitive and key customers, which fit into the Land use category described in [30]. On the other hand, an almost similar analysis performed in [22] suggested four matrices for analyzing the consequences of pipeline failure. These included (i) demand; which was described to compare the system pressure against demand at each node, indicating that higher impacts were experienced by high-demand nodes during failure events. (ii) Population; which indicated the number of people likely to be affected by the failure. (iii) Land use and (iv) economic loss matrices, representing activities likely to be affected and financial implications of failure respectively.

Consideration of financial impacts of failure stands out as quite profound in almost all of the abovementioned analyses [2, 13, 16], however, majority of failure impacts are not easy to quantify [2, 31, 32]. In addition, utilities may not be willing to provide some financial details about their operations [21, 31], as they may be considered confidential. Therefore, relatively non-intrusive approaches that may be used as surrogate inputs should be embraced by researchers, developers and utilities at large. In Table 2, a classification of some of the consequences of failure; and respective inputs that they may represent are outlined. These surrogate inputs are none-intrusive and do not contain utilities sensitive information but are however, still adequate enough for failure modeling.

Table 2. Classification of the consequence index of pipeline failure

Index	Description	Represented inputs	Other possible representations
Pipe diameter (PD)	– Refers to the carrying capacity of the pipe – Commonly measured in millimeters (mm)	Amount/value of water loss, pipe usage/service level, environmental damage	Resistance to pressure – Construction standards – Manufacturing method – Pipe resilience
Activity Pressure (AP)	– Refers to the various activities carried out in the regions serviced by the pipe, commonly known as the degree of land usage around the pipe – Also quantified by the amount of commercial or agricultural premises served by a pipe	Activities likely to be affected by the failure, Sensitive or key customer base, secondary damage, service disruption cost, recovery cost	– Operating pressure – Pipe diameter – Private and public property damage – Service demand – Public image – Pipe use – Environmental damage
Population Pressure (PP)	– Refers to the number of persons served by a pipe section – Mostly quantified by the number of households surrounding the pipe segment or a rough estimate of a community's population density	Cost of service disruption, social costs, quantity of persons affected by failure, Health risks	– Pipe usage – Pipe diameter – Public health risk – Service demand – Operating pressure – Quality of life – Public image – Conceivable amount of fatalities
Operational pressure (OP)	Represents the weight of service demand from a pipe	Demand, pipe use, failure rate, amount of water loss	– Pipe pressure – Water velocity – Construction standards – Manufacturing method – Pipe resilience

6 Relevance of This Classification in Uncertainty Modeling

Pipeline failure process is a subject that is not fully comprehensible [21], given the level of complexities and uncertainties it is accompanied by. Likewise, availability of data regarding the failures and their subsequent consequences is daunting. Existing data therefore, tend to be either deficient or with defective information [3, 20]. Additionally, there is lack of a standard procedure for estimation, categorization and quantification of failure consequences. These challenges have, in a great way contributed to uncertainties in available data. However, availability dynamic models like Bayesian Networks (BNs), that are able to incorporate expert knowledge together with auxiliary information, make it possible to handle these inherent uncertainties, thereby enhancing precision in pipeline failure prediction [30, 33].

6.1 Overview of Bayesian Networks

BNs are graphical models used for reasoning under uncertainty. For this course, they depict a system as a network of interacting variables, with the variables presented as *nodes* and the interaction among them presented as *arcs* joining the nodes to indicate causal dependencies among them [33–35]. These interactions are the aspects used to determine the eventual behavior of a given system [35, 38], and are also instrumental for representation of uncertainty.

Uncertainty in this case, is determined by associating probabilities with the links between the variables [36]. These probabilities, however, must conform to three basic rules; (i) $P\ (A)$, the probability of an event A must be between 0 and 1. (ii) $P\ (A) = 0$

means that A is impossible, while $P\ (A) = 1$ means that A is definite. (iii) $P\ (A \text{ or } B) = P\ (A) + P\ (B)$, provided A and B are disjoint [36]. Conditional probabilities are then computed and later updated using the Bayes, theorem, as shown in Eq. (1). Given n number of mutually exclusive variables $X_{i\ (i\ =\ 1,\ 2,\ \ldots,\ n)}$ and observed data Y, updating of probabilities is done by:

$$P(xi|Y) = [P(Y|Xi) \times p(Xi)]/[\Sigma jp(Y|Xi)P(Xj)] \tag{1}$$

Where p (X|Y) is the posterior occurrence probability of X on condition that Y occurs, p(X) is the prior occurrence probability of X, p(Y) for marginal (total) occurrence probability of Y which is considered constant given the data at hand, and finally p (Y|X) representing the conditional occurrence probability of Y on condition that X occurs, also viewed as the likelihood distribution. These indexes can therefore, be plotted systematically to produce understandable causal dependencies in pipe failure. The classification also accommodates incorporation of non monetary consequences in modeling pipeline failure for extended decision making.

7 Conclusion and Future Work

In this paper, a review of the causes of failures along pipelines, as well as the associated consequences of these failures has been conducted. The causes of pipeline failure are found to be widely distributed and dependent on fluctuating natural and man-made conditions. Similarly, the consequences are just as diverse as the respective causes. An open classification of these consequences has also been done, indicating the different surrogate inputs that may be used in situations where availability of sensitive information may not be possible. These inputs however, may only be applicable when modeling techniques applied are fit enough to handle data uncertainty.

Therefore, following the above classification, BN models will be produced and computed accordingly for precise failure prediction. The classification of the failure consequences performed herein however is not exhaustive. Therefore, extended research focusing on the categorization of failure impacts is highly recommended. Additionally, further research that aims at possible quantification of these impacts is also necessary as this will in a point of fact; reveal the proper magnitude of pipeline failure.

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