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REVIEW ON CORROSION OF UNDERGROUND PIPELINES USING RELIABILITY

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ABSTRACT

This paper reviews the literature about the concept of reliability used for corrosion of underground pipelines. The study of different factors responsible for corrosion has been discussed under this paper. The literature reviewed includes the research that falls under corrosion such as surveys and historical analysis of buried pipelines and laboratory studies aimed to duplicate soil exposures etc. It also includes the study pattern of reliability under failure and repair mechanism using graphs. Different kinds of distribution have been discussed for the problem based on the models falling under discrete and continuous situations.

Keywords: Corrosion, Underground pipelines, Reliability Analysis.

I. INTRODUCTION

Corrosion is one of the most common forms of deprivation in pipelines that affects cyclic and static strength of a pipeline simultaneously. Currently, offshore and onshore pipelines are one of the safest and efficient means of transport of oil and gas. There is a chance as a pipeline ages, it can be significantly affected by deterioration mechanism which may lead to increase in a number of accidents and structural integrity [1]. After 15-20 years of service, it had observed an incident of failure due to corrosion or stress cracking of high pressure in a pipeline[2]. Pipeline corrosion defects, size, location and extent can be detected by intelligent online inspection tools. Nevertheless, the inspection tools are not perfect and the degree of detection ambiguity remains. In 2000, Riemer et al. [3] said that transportation of gasoline products and petroleum had initiated in early 20th century using buried steel pipelines over the long distances. Underground flexible pipes are intended to bear the exterior soil and other loads, buckling and resist deflection with suitable factors of protection to look out of uncertainties in design values [4]. M.A.L. Hernandez-Rodrıguez (2007) et al. [5] presented the failure scrutiny of an APL 5L X52 steel section of a pipe which is situated next to natural gas abstraction plant. The T-shape of pipelines gets damage under unknown circumstance. This resulted in an exposure of the fresh steel surface to the extremely destructive environment that overcomes inside the pipeline. Corrosion is identified as most dominating method of deterioration process and recognized as a major cause of loss containment for offshore. Failure of corrosion represents an important proportion of the total number of failures of natural gas pipelines [6]. Probes that can detect internal and external in real time scenario before failure occurs in the buried pipeline will enhance the transmission pipeline reliability. Pipeline reliability had received great attention as the prediction of small failure probability is very less till date. Estimation of a pipeline is the fundamental process to analyze the pipeline reliability. No such technique or algorithm is available to estimate the reliability of the buried pipeline. It is given by an integral of the high dimensional uncertain parameters. Some of the methods to evaluate the

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reliability are FORM [7] (First-Order Reliability Method), SORM (Second-Order Reliability Method), PEM (Point Estimation Method) and MCS [8, 9, 10] (Monte Carlo Simulation) etc. are reported in the literature [11]. The random features of prevailing parameters in the real pipeline have motivated many researchers to assess the failure probability of pipelines with or without corrosion damage. The first reliability assessments were based on the modified B31G [12, 13] criterion and used FORM [14] based methodology and later the first as well as second order (FOSM) [12] reliability method [1, 15]. It is examined that the assessment of the corrosion risk is done by monitoring the reliability of the underground pipeline. The corrosion risk accomplished with the help of inspection and monitoring program should be assimilated into the inclusive activity schedule of an organization. This paper focuses on the literature available on reliability analysis of the buried pipeline under corrosion to avail the fact which is the most critical failure modes and how to overcome these failures.

F. Caleyo (2002) et al. [8] provided the study of first-order second-moment iterative reliability method, Monte Carlo [16] integration technique and FOTSE (First Order Taylor Series Expansion) [17] of the limit state function so as to estimate the failure probability associated with the flaws over time. Sensitivity analysis had been widely applied in a broad range of sciences for example, environmental sciences, chemistry, risk analysis, etc. [18]. The sensitivity of the reliability based on MPP (Most Probable Point) depends on a linearization of the limit state function. For nonlinear performance function, linearization will cause weak precision in the reliability and the reliability sensitivity evaluation.

II. FAILURE MODELS THEORIES

For a buried pipe erection, a number of probable failure modes are quiet high for systems with failure definition. It is true despite simplification executed by assumptions, such as finite number of failure elements at a certain point of the structure and only making an allowance for the proportional loadings. All manners of underground sewer pipes either flexible or rigid rely on the backfill properties to allocate the loads into the bedding. The failure criteria are implemented due to the loss of physical strength of the pipelines by external loadings and these failure criteria are influenced by corrosion through reduction of the pipe wall thickness. The failure criteria of flexible pipes are characterized as:

1. Extreme Deflection
2. Buckling
3. Wall Thrust
4. Bending Stress and Strain
5. Metal Pipes Corrosion

2.1 Extreme Deflection

Metals that are used in the buried pipelines are concrete, metal or plastics, e.g. ductile iron, steel, copper or cast iron. Plastic pipes tend to be resistance to corrosion which is a variable and continuous process [19, 11]. Metal pipes are corroded under certain environmental conditions, based on the properties of the pipe and the soil near the pipe wall. Deflection is a change in inner diameter that occurs when the load is applied to a flexible pipe. It is computed in term of the proportion of the vertical decrease in diameter (or horizontal increase in diameter Δ_y) to the pipe actual diameter. The deflection is given by as [11, 19, 20] in eq. (1)

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$$\Delta_y = \frac{K(D_l W_c + P_s)D}{\left(\frac{8EI}{D^3} + 0.061E'\right)} \quad (2)$$

Mean Diameter = $D_j + 2c$ (3)

Soil load, $W_c = \gamma_s H$

Live load,

$$P_s = \frac{W_s I_f}{L_1 L_2} \qquad \text{Where, } I_f = \begin{cases} 1.1 \ \forall \ 0.6\text{ m} < H > 0.9\text{ m} \\ 1 \ \forall \qquad H \geq 0.9\text{m} \end{cases} \quad (4)$$

In eq. (1), K = Deflection coefficient, D_l=Deflection lag factor, E= modulus of elasticity, I= Moment of inertia per unit length and E'=Modulus of soil reaction.

In eq. (2), D_j = Inner diameter, c = Distance from the inner diameter to the neutral axis

In eq. (3), γ_s = Unit length,

In eq. (4), W_s= Wheel load, I_f=Impact factor, L_1 and L_2 are width of the loads parallel and perpendicular to the direction of travel.

2.2 Buckling

Due to external loading from the external hydrostatic pressure and soil pressure leads to internal deformation known as buckling [11]. It is an early failure during which pipe is not up to maintain its unique spherical shape when the tangential compressive stress level attains the limit value and the distortion is occurring unstably. The actual buckling pressure for the flexible pipe, p can be calculated [19, 21] in the equation (5):

$$p = R_w \gamma_s + \gamma_w H_w + P_s \quad (5)$$

Water buoyancy factor, $R_w = 1 - 0.33\left(\frac{H_w}{H}\right)$ (6)

Here, γ_w=Unit weight of water, H_w=Height of the groundwater above pipe spring line and P_s = live load defined in eq. (5)

The critical buckling pressure is given by:

$$p_{cr} = \frac{1}{F_s}\sqrt{32 R_w B' E' \frac{EI}{D^3}} \quad (7)$$

In eq. (6), F_s= Design factor.

Empirical coefficient of elastic support,

$$B' = \frac{1}{1+4e^{-0.213H}} \quad (8)$$

2.3 Wall Thrust

Wall Thrust/wall crushing/ Hedge Thrust is characterized by localized acquiescent when the wall stress reaches up to the stress of the pipe material. If pit depth is not adequate, then the wall of the pipe is affected due to the earth and surface loading including soil, traffic, and hydrostatic loads. Due to the installation of only dead loads, the computations of wall thrust analysis, consider the long term material properties. However, in case of both live and dead loads, the two analyses are required [20]. During the process, interpret both dead and live loads

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and employs the short term material assets. Second, only interpret the dead loads and employ long-term material properties throughout the process.

The estimation of the critical wall thrust [21] is given in eq. (9)

$$T_{cr} = F_y A_x \emptyset_p \tag{9}$$

where, F_y=minimum tensile strength of the pipe, A_x=cross-sectional area of a pipe per unit length, $\emptyset_p$=capacity modification of a pipe.

The estimation of the wall thrust is given in eq. (10)

$$T = 1.3(1.5W_a + 1.67P_s C_l + P_w)(OD/2) \tag{10}$$

Soil arch load,

$$W_a = (P_{sp})(V_{af}) \tag{11}$$

Geostatic load,

$$P_{sp} = \gamma_s(H + 0.11 * 10^{-7}(OD)) \tag{12}$$

In eq. (10), P_s=live load, C_l=live load distribution coefficient, P_w= hydrostatic pressure and OD= outer diameter of pipe.

Vertical arching factor, $V_{af} = 0.76 - 0.71\left(\frac{S_h - 1.17}{S_h + 2.92}\right)$ (13)

In eq. (13) S_h is hoop stiffness factor.

2.4 Bending Stress and Strain

In order to ensure that whether the material is under capability or not, an estimation of the bending stress and strain is done. The safety of the pipe is ensured when bending stress [20] should not exceed the ductile strength of the measurable, along this; the longitudinal bending strain should not exceed the acceptable strain limit of 5% for polythene pipe and 0.15-2% for flexible pipe.

Bending stress [21],

$$\sigma_b = \frac{2D_f E\Delta_y y_0 S_f}{D^2} \tag{14}$$

Bending strain, $\varepsilon_b = \frac{2D_f \Delta_y y_0 S_f}{D^2}$ (15)

where, S_f = Safety factor, D_f= Shape factor and y_0= Distance as of the centroid of the pipe.

2.5 Metal pipe corrosion

The damage of pipe wall width due to corrosion can be a comparatively localized and uniform in extent [22, 23]. Initially, the rate of thickness of the wall is high due to the porous form of the corrosion product and has poor protective properties. It is evident to suggest that corrosion is a self-preventing process, as corrosion continues, the protective assets of products like iron oxide improves over time and corrosion rate decreases. Rajani et al. [24] industrialised a corrosion model to predict the soil corrosion pit depth over an exposure time period of buried cast iron pipe. The model is capable of determining the pit depth for low corrosive soil. The pit depth (d) is given by [25, 26]:

$$d = KT^n \tag{16}$$

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$$d = a\tau + k(1 - e^{-c\tau}) \qquad (17)$$

where, a = minimum corrosion rate in mm/year, k are corrosion parameters in mm and τ =exposure time period for cast iron pipe. The feasible ranges for $0.0042 \leq a \leq 0.0336$, $1.95 \leq k \leq 15.6$ and $c = 0.058$.

Y. Katano et al. [27] expressed the pit depth (η) as:

$$\eta = \gamma t^{\alpha} \qquad (18)$$

where't' is the time

Pitting rate, $d = a + kce^{-c\tau}$ (19)

III. CORROSION AND RELIABILITY

Corrosion of cast iron cemented lined pipes involves thinning, pitting, and graphical changes. From the literature, it has been concluded that the external soil features that effect the corrosion of the buried pipes contain: moisture content, diversity of the soil, resistivity, and degree of aeration, microbiology, temperature [28]. For simplifying the problem, the structural reliability of the subversive sewer is first estimated and risk-cost optimization [20] is done to predict the optimal preservation or renewal time for the reliability analysis and LCC (life cycle cost). The Reliability of a unit is the probability that the unit performs its proposed function for a certain period of time under the specified working conditions. In a simplest form, the Reliability means the probability that the unit performs without any failure in a given interval of time. Reliability stresses on four major elements: probability, time, intended function and the functioning environment. If T is the failure time of a unit, then the probability of times

$$R(t) = P(t > t) = 1 - P[T \leq t] = 1 - F(t) \qquad (20)$$

A reliability of any unit is always varied between zero and one, i.e. $0 < R(t) < 1$

If no measures are encountered then the defect of the corrosion is expected to rise with an increased exposure period. The evolution of the corrosion defect is determined by the characteristics of pipe measurable properties such as surroundings and when the fluid is elated [15]. Southwell et al. (corrosion of metals in tropical environments) suggested that the exposure period is inversely proportional to the evolution rate, but the overall dimension of the corrosion defect increases and this poses a greater risk to pipeline reliability. Based on this assumption, steady state growth is as follows:

Steady state corrosion in the path of depth,

$$R_d = \frac{\Delta d}{\Delta t} \qquad (21)$$

Steady state corrosion in the path of length,

$$R_L = \frac{\Delta L}{\Delta t} \qquad (22)$$

where Δd = difference among the two defect depth measurements, Δt = difference between the two defect time measurements, ΔL = difference between the two defect length measurements.

Estimation of the defect depth (d) is done by using eq. (23)

$$d = d_0 + R_d(T - T_0) \qquad (23)$$

Estimation of the defect length (L) is done by using eq. (24)

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$$L = L_0 + R_L(T - T_0) \quad (24)$$

where d_0 and L_0 respectively are measured depth and length of the defect at time T_o. Corrosion in buried pipeline results in the loss of effective wall thickness. Accordingly, the loss of the wall thickness is modelled empirically by a power law given below [29].

$$P = kT^n \quad (25)$$

VI. RELIABILITY ANALYSIS WITH GRAPH

4.1 Reliability with failure

Fig. 1 clearly depicts that initially the failure rates λ_i are high, but they drop rapidly by time. The exponential-decaying-like behaviour of the failure rate is identified as infant mortality or wear-in. It indicates that earlier failures are integrally present in the product before it is tie up in service. Products that were survived in wear-in period are estimated not to have the fatal defects at the beginning, or to have fewer, lesser defects at the release. The failure reliability is fitted using a smooth function $\lambda(t), \forall\, 0 < t < \hat{\lambda}$. $\lambda(t)$ is the failure rate function. As shown that $\lambda(t)$ is analytically related to $f(t)$, the time to failure probability functions of the product.

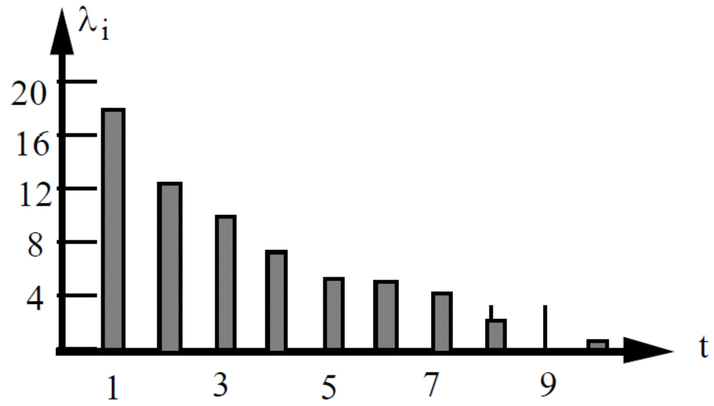

Figure1. Reliability vs. Failure Rate

4.2 Failure Rate

The failure rate function $\lambda(t)$ is critically connected to the time-failure probability distribution $f(t)$. This relationship can be readily recognized by examining $f(t)$ graphically, as shown below:

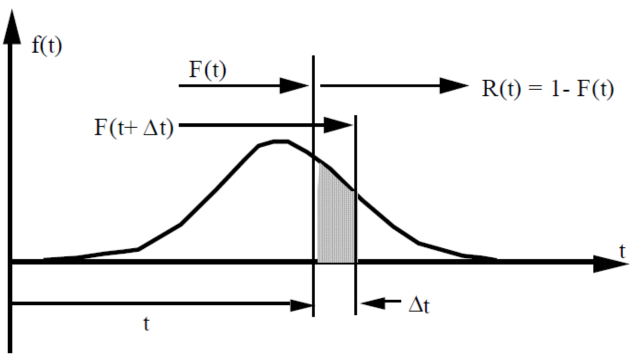

Figure 2. Bell Shape Curve

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The bell-like curve demonstrated the probability density function $f(t)$; the area below the bend from 0 to t is F (t); the range under the curve from t to ∞ is the probability of survival is denoted by:

R (t) =1-F (t) (26)

Δ (t) is the little augmentation in time from t. Consider the partial likelihood of failure that happens inside Δ (t). It is clearly shown in figure 2, that the fraction of failure occurs when the product has survived the era from 0 to t. Subsequently, the probability of the item that fails within $\lambda(t)$ is a conditional, indicated by $\{f(t)\Delta t\}/R(t)$. The time rate of change of that probability is the failure rate at time t given by $\lambda(t)$ thus:

$$\lambda(t) = \{f(t)\Delta t \,/\, R(t)\}/\Delta t = f(t)/R(t) \quad (27)$$

Eq. (27) is the formal relation between λ (t) and f (t). In general, one wishes to obtain f (t) when λ (t) is known. To this end, we note that

$$f(t) = \frac{dF(t)}{dt} = \frac{d[1-R(t)]}{dt} = \frac{-dR(t)}{dt} \quad (28)$$

$$\text{And, } \lambda(t) = \frac{-\left[\frac{dR(t)}{dt}\right]}{R(t)} \quad (29)$$

$$R(t) = \exp^{-\int_0^t \lambda(\tau)\,d\tau} \quad (29)$$

Now eq. (26) become

$$f(t) = \lambda(t)\exp^{-\int_0^t \lambda(\tau)\,d\tau} \quad (30)$$

$$\mu = \text{MTTF(Mean Time To Failure)} = \int_0^\infty t\, f(t)\,dt = \int_0^\infty R(t)\,dt \quad (31)$$

4.3 Reliability Repair Graph

The variety of working to a failed state is called failure although the variety from an inability toward a working state is allowed to as repair. It is additionally expected that repairs take the part or frame work back to another condition. This sequence proceeds with the repair to failure and the inability to-repair process; and afterwards, rehashes again and again for a repairable frame work. Reliability (for non-repairable items) can be characterised as the likelihood that a thing will play out a characterised work without failure under expressed conditions for an expressed time frame. One should handle the idea of probabilities to understand the idea of reliability. The mathematical estimations of both unwavering quality and trickiness are communicated as likelihood from 0 to 1 and have no units.

4.4 Repairable and Non-repairable Items

It is significant to differentiate between repairable and non-repairable items when anticipating and calculating reliability. Non-repairable items are mechanisms or arrangements, for example, a transistor, bulb, rocket motor, etc. Their reliability is a continuation probability above the items estimated life or over a limited duration of time during its life, when there is a chance of failure. During the life of the system or component, the fast anticipation of the failure is called the hazard rate/failure rate r (t). Life rates such as mean time to failure (MTTF) explained before are used to characterize non-repairable items.

4.5 Repairable Items

In 1998, fifteen specialists from establishments in the Netherlands, UK, Italy, France, Germany etc. or many other countries [30] took part in the investigation of disappointment recurrence of buried pipelines per kilometre

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year, as an element of pipe and natural attributes. For repairable things, dependability is the likelihood that failure can't happen in the day and age of intrigue; or when more than one failure can happen, unwavering quality can be characterised as the failure rate, λ, or ROCOF (the rate of occurrence of failures). Given repairable things, unwavering quality can be portrayed by MTBF as clarified above, yet just the situation being what it is of steady failure rate. In addition, the stress for availability A (t) of repairable things since repair requires some investment. Availability is mixed by the degree of an event of failure (λ) or MTBF in addition to maintenance time; where support can be remedial (repair) or precaution (to decrease the possibility of failure). A (t) is the likelihood that a thing is in an operable state whenever

Availability $A(t) = \frac{MTBF}{MTBF+MTTR}$ (32)

A few frameworks were viewed as both non-repairable and repairable such as missile. It is repairable during the underground test, and yet turns into a non-repairable framework when it let go. Failure rate (λ) is connected freely to non-repairable things. It is truly implied in a repairable framework which contains a section, i.e. some fragment will add to the general frame work disappointment rate by the expressed portion failure rate. The part being non-repairable can't have a failure rate [31].

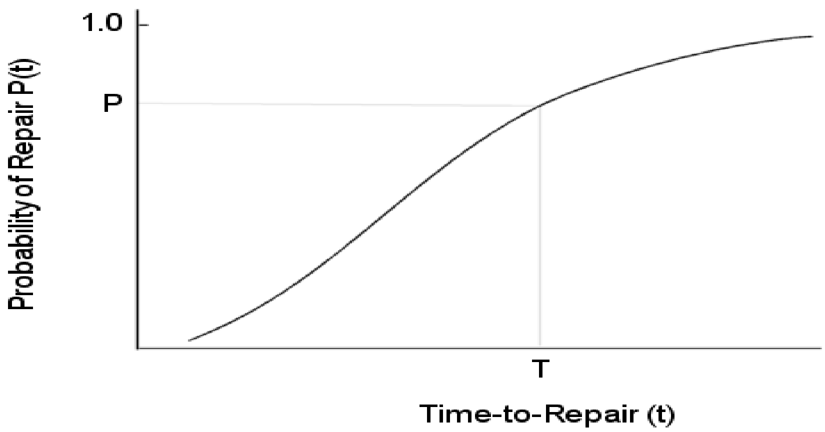

Fig.3: Reliability vs. Repair rate

V. PROBABILITY DISTRIBUTION MODELS IN RELIABILITY

The Probability distribution is a function that provides the probability of occurrence of different possible outcomes in a testing. Random variable and probability distribution random variables are described in discrete and random form. So, different distributions are used according to the data available as discrete or continuous one. Two distributions named exponential distribution under continuous and geometric distribution under discrete cases are studied as there is a close connection between these two distributions. The Exponential distribution is the continuous analogy of geometric distribution and the discrete component of exponential distribution leads to geometric distribution.

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5.1 Exponential Probability Density Function :

Let 'Y' be a continuous random variable and known as exponential distribution [32] with parameter $\lambda > 0$ given as

$$f_y(y) = \begin{cases} \lambda\, e^{-\lambda y} & Y > 0 \\ 0 & \text{Otherwise} \end{cases} \quad (33)$$

5.2 Geometric Distribution

Let 'Y' be a random variable. Then 'Y' is supposed to be geometric distribution if it accepts only positive values and probability mass function is given by:

$$P(Y=y) = \begin{cases} q^{y}\, p;\ y = 0,1,2,\ldots\ldots;\ p \in (0,1]\ ;\ q = 1-p \\ 0 \quad ;\text{otherwise} \end{cases} \quad (34)$$

VI. CONCLUSION

The literature has been reviewed for the study of reliability concept used under the corrosion for underground pipelines. The reliability behavior has also been studied for repair and failure situations.The scope of this paper is to present the effects of boundary conditions, failure models for buried pipelines on failure prediction by using a failure probability model and reliability analysis for repairable and non-repairable materials.

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