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RESEARCH ARTICLE OPEN ACCESS

Reducing Pipeline Corrosion in Oil and Gas Industries Using Ant Colony Optimization Techniques Agents

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Abstract:

This paper aims at developing a model for the reduction in oil pipeline corrosion in oil and gas industries using ant colony optimization techniques. The main objective of the study is to examine the reduction of pipeline corrosion in oil and gas industries using ant colony optimization techniques. The specific objectives are; to develop mathematical model to reduce the oil pipeline rupture risks and oil spill probability; to design a MATLAB Simulink model for reducing oil and gas pipeline corrosion using ant-colony optimization. In this paper ant-colony based models were developed to assess API X46, X60 and X80 oil pipelines containing multiple corrosion defects, which were longitudinally aligned, circumferentially aligned or overcome with each other. The defect size and the grade of oil pipeline were considered to evaluate the interaction between adjacent defects. Ant-colony models enabling predictions of the failure pressure of pipelines containing a dent associated with a corrosion defect were also developed. In addition, a failure pressure-based criterion to properly assess the interaction of the dent and its adjacent corrosion feature was established. The mutual interaction between the adjacent corrosion defects affects not only the local stress and distribution, but also the electrochemical corrosion rate, due to the so-called Mechano-Electrochemical (M-E) effect. Due to the existence of the M-E effect, a new criterion is proposed to determine whether the mutual interaction exists between the adjacent corrosion defects, i.e., on the ratio of the anodic current density at the defect adjacency to that of the non-corrosion region on the oil pipeline body.

Keywords — **Corrosion, Ant-Colony Optimization, Pipeline, Matlab/Simulink, Defects**

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I. INTRODUCTION

Major pipelines across the world transport large quantities of crude oil, natural gas, and petroleum products (Husseini, 2018). These pipelines play an important role in modern societies and are crucial in providing needed fuels for sustaining vital functions such as power generation, heating supply, and transportation. In light of the hazardous properties of the products being transmitted through these pipelines, a ruptured pipeline has the potential to do serious environmental damage (Achebe et al., 2012). This problem is further compounded by the fact that many developing countries have not established proper guidelines and standards for the design, construction, and operation of major oil pipelines. This study concerns the analysis of oil pipeline corrosion in Nigeria with the aim to undertake a desk study to evaluate the procedures for pipeline maintenance and contingency plans for addressing oil pipeline failures in Nigeria using ant-colony optimization techniques. The risk associated with pipeline in terms of safety of people, damage to the environment and loss of income has been a major concern to pipeline integrity managers. The first ant colony optimization (ACO) called ant system was inspired through studying of the behaviour of ants in 1999 (Sallim et al., 2006). An ant colony is highly organized, in which one interacting with others through pheromone in perfect harmony. Optimization problems can be solved through, simulating ant's behaviours. Since the first ant system algorithm was proposed, there is a lot of development in ant colony optimization. In ant colony system algorithm, local pheromone is used for ants to search optimum result. However, high magnitude of computing is its deficiency and sometimes it is inefficient. Stutzle and Hoos (2000) introduced MAX-MIN Ant System (MMAS) in 2000. It is one of the best algorithms of ant colony optimization. It limits total pheromone in every trip or sub-union to avoid local convergence. However, the limitation of pheromone slows down convergence rate in MMAS.

In optimization algorithm, it is well known that when local optimum solution is searched out or ants arrive at stagnating state, algorithm may be no longer searching the global best optimum value (Wu et al., 2023). In their algorithms, when ants arrived at local optimum solution, pheromone will be decreased in order to make algorithm escaping from the local optimum solution. When ants arrived at local optimum solution, or at stagnating state, it would not converge at the global best optimum solution. In this paper, a modified algorithm, multi-colony ant system based on a pheromone arithmetic crossover and a repulsive operator, is proposed to avoid such stagnating state (Dorigo et al., 2006). In this algorithm, firstly several colonies of ant system are created, and then they perform iterating and updating their pheromone arrays respectively until one ant colony system reaches its local optimum solution. Every ant colony system owns its pheromone array and parameters and records its local optimum solution. Furthermore, once an ant colony system arrives at its local optimum solution, it updates its local optimum solution and sends this solution to global best-found centre. Thirdly, when an old ant colony system is chosen according to elimination rules, it will be destroyed and reinitialized through application of the pheromone arithmetic crossover and the repulsive operator based on several global best-so-far optimum solutions. The whole algorithm implements iterations until global best optimum solution is searched out.

II. METHODOLOGY

The methodology employed for this research integrates the application of the ant colony optimization algorithm as a means to mitigate corrosion in pipelines. The process commenced with the development of an oil spillage probability formulation model. This model served as the foundation for understanding the potential risk of corrosion-related oil spillage occurrences within the pipeline system. Subsequently, the researchers implemented the ant colony algorithm, leveraging its capacity to simulate the behavior of real ant colonies seeking optimal paths. In this context, the algorithm was tailored to identify and target areas susceptible to corrosion, thereby facilitating the reduction of corrosion rates and the associated risks of oil spillage. By leveraging the collective intelligence of the algorithm, the paper aimed to enhance the overall resilience and longevity of the pipeline infrastructure, emphasizing the crucial role of intelligent algorithms in the realm of corrosion management and preventive measures within industrial settings.

A. Corrosion Reduction Model And Oil Spill Probability

This paper proposes a new model for oil-gas pipeline problem that is capable in reduce corrosion and addresses in the real situation. The mathematical model (Uthman, 2011; Adetunji, 2013; Emami, 2011)

$$minimize \sum_{i=1}^{n} Tc_i = \sum_{i=1}^{n} (LSD_I * cs) \qquad (1)$$

Where LSD_I is the length of the pipe connecting two wells (km) and CS represents the cost of one pipe per km the following was used to interpretation was used to represent the real issue.

Interpretation 1-There exists an obstacle between two wells, this obstacle will lead to corrosion,W_i and W_j if the link between them is null as equation in (2) below. In this case, the distance between is zero as stated in (3).

$$\text{Link } (i, f) = \emptyset \qquad (2)$$

$$D(W_iW_j) = 0, \forall\, link(i,j) = \emptyset \tag{3}$$

Interpretation 2: The distance between is zero for the same well given by

$$D(W_iW_j) = 0, \forall\, i = j \tag{4}$$

Interpretation 3: The connection between two wells, is possible in one direction only given by

$$D(W_iW_j) = 0, \forall\, D(W_iW_j) = d_i d_l \neq 0 \tag{5}$$

The distance W_i and W_j between interpret in (5) is given by

$$D(W_iW_j) = \sqrt{(x_i - x_l)^2 + (y_i - y_l)^2} \tag{6}$$

The new proposed model as below which is programmed using MATLAB software

*Ps*eudocode for New Proposed model

```
Input: WLT(X,Y) $\in R^{2*n}//$ $location\ table\ for\ all\ wells$
Output: shortPathTable
Begin:
Calcula$teD_{table} \in R^{n*n}$
For$i = 1{:}n$ Do // $i = l, 2, n$;
For $j = 1{:}n$ Do
If corrosion $(i,j)$ = 1 THEN
$D(I,J) = \infty$
ELSE
$D(I,J) = SQR((X_i - x_j)^2 + (y_i - y_l)^2)$
End IF
Next
For well.$id = 2{:}n\ Do$
Determine short path for well (well.id)
Set $X \leftarrow well.id$
S_ID = Short Path(Well.id{D}) $\in R^{1*1}$
SET Well(well.id). Link = S_1D
SET D (Well.Id,S_ID)= ∞
SET $\gamma \leftarrow S\_ID$
Z = Short Path (Y, {D})
SET D(X,Z) = ∞,D(Z,X)=∞
ShortPathTable(Well. Id) =Well(Well. Id). Link
Next
End Algorithm
```

B. Development of Ant Colony Algorithm To Reduce the Oil Pipeline Corrosion and Oil Spill Probability

The ACO algorithm is an exploratory method capable of solving complex problems by looking for optimal solutions in the graphs within a range of possibilities. This algorithm mimics the natural behaviour of the ants in the search for food where ants come out to find food, and when it does, a chemical known as pheromone is released on the way back to the colony. The rest of the ants will pick up the scent and follows the same path. The more ants follow the path, the greater the concentration of the pheromone, which causes the long path to disappear as this material rapidly evaporates. In the end, there is only one path followed by the ants, which is the shortest path. On this basis, this algorithm is chosen for comparison purpose with the proposed algorithm. The standard ACO rule $p_{i,j}^k$ mentioned in equation (7)

$$p_{i,j}^k = \frac{[T_{i,j}][\gamma_{i,j}]^\beta]}{\sum_{\mathrm{i}}^{\mathrm{k}} zcallowed[T_{i,j}]^\beta][\gamma_{i,j}]^\beta]} \tag{7}$$

where $k \in \{1,2,3, \ldots \ldots . m\}$ is the number of ant, at node i . $p_{i,j}^k$ is the probability with which ant k chooses to move from node i to node j . $\gamma_{i,j}$ represents the amount of pheromone along the transition from node i to j. α is the parameter that controls the influence of $\gamma_{i,j}$, and $\gamma_{i,j}$ is the desirability of the node transition ij (a prior knowledge, typically $\frac{1}{d_{ij}}$ where d is the distance and $\beta \geq 1$ is a parameter that controls the influence of $\gamma_{i,j}$. While $\gamma_{i,j}T_{i,j}$ represents the attractiveness and trail level for the other possible node transition pheremonc update. When all the ant have complete a solution, trails are updated by $\gamma_{i,j} \leftarrow (1-\rho)\,\gamma_{i,j} + \sum_k^{\mathrm{i}} \Delta\tau_{ij}^k$, with

$$\Delta\tau_{ij}^k = \begin{cases} \frac{q}{l_k} & \text{if ant uses curve } ij \text{ in its tour} \\ & 0 \end{cases} \tag{8}$$

Where

l_k is the cost of the k_{th} ant's tour and q is a constant

Pseudo code for Ant Colony Algorithm

```
Input:WLT(X Y)∈ $R^{n*n}$// location Table all the wall
Output:ShortPathTable
Begin
Calculate $D_{Table} \in R^{n*n}$
For it =1: maxIt
    For k = 1 :nAnt
        Ant(k).Tour=randi([1nVar]);
        For I=2:nVar
            I= ant(k). Tour(end);
            P=tau(I,:)^alph.*eta(I^beta;
            P(ant(k).Tour)=0;
            P=P/Sum(p)
            J= RouletteWheelSelection(P)
            Ant(k). Tour=[ant(k).tourj]
        Ant(k).Cost = CostFunction(ant(k).Tour;
        If ant(k).cost<bestsol.cost
            BestSol=ant(k)
    Update Phromones
    For K=1:n Ant
        Tour = ant(k).tour
        Tour=[tour tour(1)];%#ok
        For l=1;nVar
            I= tour (1)
            J = tour (l+1)
            I = tou(ij) =tau(ij)+$\frac{Q}{ant(k).cost}$
Next
End algorithm
```

C. System Integration

The integration of the Ant Colony Algorithm for corrosion detection with the proposed algorithm for reducing oil pipeline corrosion and spill probability forms a comprehensive strategy. The Ant Colony Algorithm identifies corrosion-prone areas by optimizing paths, considering a defined cost function representing corrosion severity. The proposed algorithm, tailored for corrosion reduction, utilizes this information to calculate distances and paths, implementing protective measures. The integration combines these results, creating a holistic corrosion management approach. It continuously adapts based on real-time or periodic monitoring, optimizing strategies and scheduling maintenance for sustained effectiveness. This integrated system provides a robust solution for minimizing corrosion impact and spill probability in oil pipelines, offering a dynamic and responsive approach to pipeline integrity and safety. The lifecycle of the system Integration is reported in Figure 1

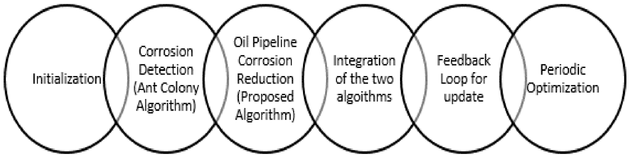

Figure 1: Lifecycle of the system integration

D. System Implementation

The developed ant-colony algorithm was implemented in the Java programming language. The Simulink model of the oil pipelines used in the case study was created using MATLAB Simulink 2018a. The study considered the properties of the X46, X60, and X80 oil pipelines. MATLAB Simulink provides Application Programming Interface (API) support for Java and C++ programming languages, enabling the loading of the Ant-colony algorithm code into its workspace for interaction with the MATLAB kernel. The Ant-colony program communicates with the MATLAB operating system object through Common Object Request Broker Architecture (CORBA) for seamless inter-object communication. This approach allowed the assessment of the performance of the proposed

Ant-colony techniques in corrosion detection and reduction for the specific oil pipelines. The simulation results were used to evaluate corrosion reduction and related factors, including the ratios of maximum von Mises stress and anodic current density concerning variations in defect depth.

III. RESULTS

To assess the impact of corrosion reduction on local maximum stress, this paper employs the maximum Ant-colony stress at a single corrosion reduction (top defect) as a reference, denoted as MaxSsingle. The stress concentration induced by overlapped defects is quantified as MaxSovercome/MaxSsingle, where MaxSovercome represents the maximum von Mises stress at the overlapped corrosion defects. Similarly, the maximum anodic current density at a single corrosion defect is labeled as MaxAsingle, and the effect of overlapped corrosion defects is evaluated through the MaxAovercome/MaxAsingle ratio, where MaxAovercome signifies the maximum anodic current density at the overcome corrosion defects.

Figure 2 illustrates the relationship between the maximum ant colony at overcome corrosion defects and that at a single defect, i.e., MaxSovercome/MaxSsingle, as a function of the ratio of defect depths, d2/d1, with d1 set at 4 mm and varying d2. It is evident that the presence of overlapped corrosion defects amplifies stress concentration compared to that at a single defect. As the d2/d1 ratio increases, signifying greater depth of the bottom defect, MaxSovercome/MaxSsingle also increases, indicating an escalation in local stress concentration with deeper bottom defects. Additionally, the impact of defect length on stress concentration is determined. The figure reveals that, at specific defect depth ratios, an increase in defect length results in elevated local stress concentration. For instance, at a d2/d1 ratio of 0.1, the maximum von Mises stress ratio is approximately 1.0 for three pairs of defect lengths (L1 and L2). However, when the d2/d1 ratio is 1.0, the maximum von Mises stress ratios increase to 1.16, 1.29, and 1.36 for defect lengths of L1 and L2, including 0.5l and 2l, and 1.5l and 3l, respectively. Therefore, as corrosion defects grow longer, the maximum von Mises stress ratio becomes larger at specific d2/d1 ratios, indicating that, while the defect depth remains constant, the length of the corrosion defect also significantly influences increased stress concentration.

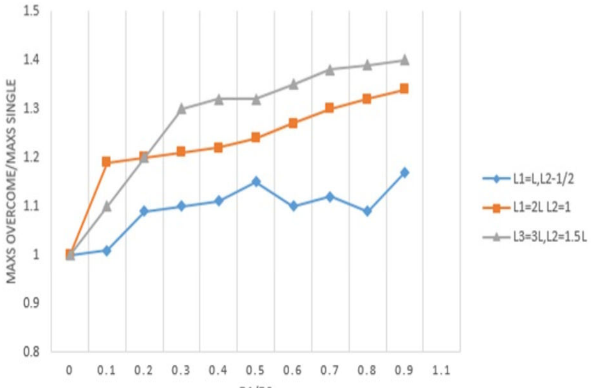

Figure 2: Proposed ant-colony ratio of the maximum ant-colony at overcome corrosion defects to that at the single defect

Figure 2 shows the proposed ant-colony ratio of the maximum ant-colony at overcome corrosion defects to that at the single defect, i.e., MaxSovercome /MaxSsingle, as a function of the ratio of the defect depth, i.e., D2/D1, where D1 is 4 mm and D2 is varied. The ratios of the maximum anodic current density at the overcome corrosion defects to that at the single defect, i.e., MaxAovercome / MaxAsingle, as a function of the defect depth, i.e., d2/d1, where d1 is 4 mm and d2 is varied are shown in Figure 3. Generally, the maximum anodic current density ratio increases with the increasing depth ratio, indicating that the presence of the bottom corrosion defect enhances the ant-colony on local corrosion growth, as compared to the single defect. With the increase of the lengths of the corrosion defects, the maximum anodic current density ratio increases rapidly at specific defect depth ratios. Therefore, the proposed ant-colony at the overcoming corrosion defects also increases with the defect length.

Figure 3 shows the proposed ant-colony model based on Ratios of the maximum anodic current density at the overcome corrosion defects to that at the single defect, i.e., MaxAovercome / MaxAsingle, as a function of the defect depth, i.e., d2/d1, where d1 is 4 mm and d2 is varied. In the figure 2, where MaxAovercome is the maximum anodic (corrosion) current density at locations with multiple corrosion defects, and MaxAsingle is the maximum anodic current density at a location with a single defect. The result takes into account the depth of the defects, which is represented by the ratio "d2/d1," where d1 is a constant value of 4 mm, and d2 is the depth of the corrosion defect. By varying the depth of the corrosion defects (d2), the model aims to understand how the ratio of anodic current densities changes as the defects become deeper or shallower.

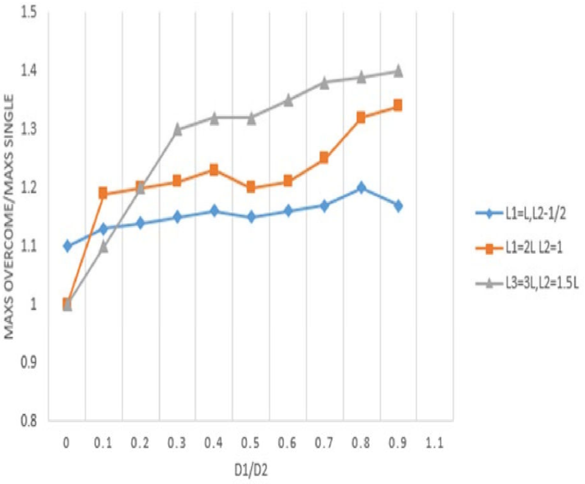

Figure 3: Proposed Ant-colony model based on Ratios of the maximum anodic current density at the overcome corrosion defects to that at the single defect

This approach is valuable in corrosion analysis because it helps assess the severity of multiple corrosion defects compared to a single defect and how this severity changes with different defect depths. The ant-colony model likely uses these ratios to guide decisions or actions in managing corrosion in materials or structures, such as determining the most critical areas for repair or monitoring based on the depth and density of defects.

IV. CONCLUSION

In this paper, Ant-colony models were developed to reduce the corrosion of oil pipeline X46, X60 and X80 oil pipelines containing multiple corrosion defects with varied geometries and orientations by assessing the mutual interaction of the defects and the effect on pipeline integrity. Generally, the reduction of pressure of corroded pipelines decreases with the increasing interaction between corrosion defects. There is little effect of the pipeline grade on the interaction between defects. The interaction mainly depends on the mutual orientation of the defects and their geometry and spacing. Compared to circumferential corrosion defects, the longitudinal defects are associated with a larger spacing where the interaction between corrosion defects exists. The circumferential spacing of corrosion defects has a smaller impact on the failure pressure of corroded pipelines compared to the longitudinal spacing. The M-E effect resulting in a more negative corrosion potential and a larger anodic current density were found at the defect adjacency compared to the uncorroded area, resulting in accelerated localized corrosion around the defects. Due to the existence of the M-E effect, the interaction rule used to determine the critical spacing of adjacent corrosion defects should be redefined due to the synergism of multiple physics fields (e.g., stress field and electrochemical corrosion field) at the corrosion defects. It was also found that, for the circumferentially aligned corrosion defects, although the interaction between them is marginal when the pipelines primarily experience the hoop stress generated by an internal pressure, it can be significant when the pipeline is under an axial stress due to ground movement. This is because the maximum von Mises stress around the corrosion defects on stressed oil pipelines is located at the area perpendicular to the direction of the stress, while the minimum von Mises stress is at the area parallel to the stress direction. Under an internal pressure, the von Mises stress of the area between the circumferentially aligned defects the lowest. However, under a tensile stress, the von Mises stress at the area between defects can be the highest. Therefore, the interactions are much more apparent, which also accelerates corrosion at the defects and their adjacency due to the M-E coupling effect.

The presence of overlapped corrosion defects results in a local stress concentration and enhanced M-E effect on corrosion defect growth. The maximum stress always generates at the corner of the bottom defect, which can exceed the ultimate tensile stress of the steel even under normal operating pressures while the stress in the pipe wall below yielding stress. The enhanced M-E effect causes an accelerated corrosion at the bottom defect, resulting in the rapid defect growth to cause pipeline leaking. The geometry of corrosion defects, especially the defect depth and length, affects local stress concentration and the M-E effect. With the increasing length and depth of either top or bottom corrosion defects, the overall stress level increases, but the effect is more apparent at the bottom defect. Similarly, the increased M-E effect due to the increasing length and depth of the corrosion defects results in a more accelerated corrosion at the bottom defect than the top one. In this work, Ant-colony models enabling the reduction of the failure pressure of pipelines containing a dent associated with corrosion feature were also developed. The interaction identification rule based on determination of the failure pressure of pipelines containing a dent with adjacency to a corrosion feature is proposed to assess the critical spacing between them to enable a mutual interaction to decrease the failure pressure. Moreover, the interaction between the dent and the corrosion feature is determined quantitatively by numerical modelling as a function of the corrosion length, corrosion depth and the dent depth

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