

Combination of High pH SCC and Near-Neutral pH SCC Models Using Bayesian Networks

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ABSTRACT

Stress corrosion cracking (SCC) continues to be a safety concern, mainly because it may remain undetected before a major pipeline failure occurs. SCC processes involve complex interactions between metallurgy, stresses, and the electrolyte chemistry beneath the disbonded coating. For these reasons, assessing SCC failure probability at any given location on a pipeline is difficult. In addition, data uncertainties make the prediction of SCC even more challenging. The complex interactions of various seemingly unrelated parameters and varying mechanisms has been addressed using Bayesian network models. Two Bayesian network models have been created to predict both high pH and near neutral pH crack growth rates. This publication presents a new SCC model that combine the previous high pH and near-neutral pH SCC models.

Key words: Bayesian network; Machine Learning, SCC Probability, Crack Growth Rate Probability

INTRODUCTION

Environmentally Assisted Cracking (EAC) of gas transmission lines constitute about 2.6% of the total number of significant incidents recorded in the U.S. Pipeline and Hazardous Materials Administration (PHMSA) database [1]. For the hydrocarbon liquid pipelines, the EAC-related incidents constitute about 1%. Although Stress Corrosion Cracking (SCC) incidents are a relatively small percentage of significant incidents, it is important to predict the location and rate of growth of SCC because of the potential for catastrophic consequences from the growth of undetected cracks. There are essentially two forms of SCC of pipelines: High-pH SCC and Near-neutral pH SCC. Of the EAC incidents reported from 2004 to 2019 in the PHMSA database, 11 were near-neutral pH SCC, 2 were HIGH PH SCC, 18 did not report the type of SCC, and 5 were other forms of EAC. SCC can be longitudinal in the form of crack colonies due to internal pressures or circumferential in cases where there is a longitudinal stress, either from girth weld residual stresses or other external bending forces. SCC of pipelines has been studied extensively, as indicated by a selection of papers [2-22]. The SCC Direct Assessment procedure [23] describes the collection of information necessary for the likelihood of SCC at a given location.

These studies indicate that SCC of pipelines arises from complex interactions of external loads, environment formed under disbonded coatings, and the potential under disbonded coating. Each of these factors, in turn, are affected by a variety of design, construction, and operational factors. Furthermore, much of the relevant data is either unavailable, sparsely available, or uncertain. Procedures for prioritizing the locations of SCC for examination focus on a subset of conditions. It was shown that Bayesian Network (BN) provides a convenient framework to integrate the diverse factors and their causal relationships leading to SCC [23, 24]. However, challenges abound in implementing BN approach for predicting pipeline SCC. These challenges include developing conditional probability tables based on mechanistic models for various domains, obtaining the necessary input data, and defining appropriate prediction metrics. The Bayesian SCC model presented in this paper combines literature data, models, and expert inputs. The inputs to the different submodels, and their outputs are discussed as well as the approach adopted in integrating them to predict SCC. The results of the work also highlight some of the existing gaps and challenges that exist.

OVERALL APPROACH

The SCC BN model is divided into 7 sections. First, the model estimates the probability of possible disbondment geometries (*i.e.* height of disbondment, length of disbondment and percentage of coating that has failed). This is done by evaluating the forces experienced by the coating from soil forces and cathodic protection current. The differential soil forces tend to shear the coating causing wrinkling or buckling of the coating. The cathodic protection currents cause local alkalinity that reduces the bond strength of the coating. The degree of disbondment is also influenced by the coating type, the age of coating, and coating application methods. For example, field-applied coatings typically have a greater tendency to disbond than factory applied coatings, all other factors being equal. Second, the model evaluates a range of possible surface potentials under the disbonded coating. The model uses CP current, location of rectifiers, soil characteristics, pipeline surface preparation, weather conditions, ON potential measurements and results from the coating disbondment model to predict surface potential. Third, the model uses topography, weather conditions, soil characteristics, and pipeline temperature to predict carbonate/bicarbonate concentrations. Fourth, the model uses both the results of the surface potential model and chemistry model to predict SCC probability by type (*i.e.* high pH SCC, near neutral pH SCC and no SCC). The effects of dents, defects, and stresses on crack growth rates are then evaluated in a failure model. The overall approach is shown in Figure 1.

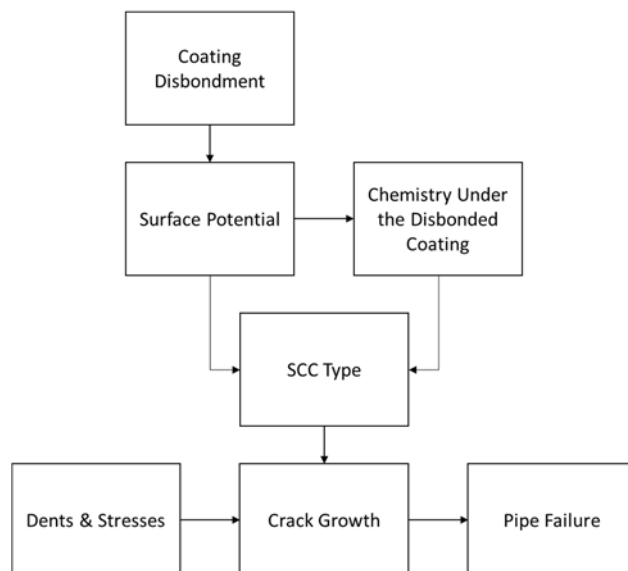


Figure 1: Overall Structure of SCC Model for Pipelines

SCC SUB-MODEL: COATING DISBONDMENT

Coating disbondment is the first step in the chain of events that leads to both high pH and near-neutral pH SCC. The disbondment can be characterized by both the length and gap of the disbonded region. The coating disbondment model is divided in two sections: coating disbondment due to soil forces applied to the coating or simply due to coating deterioration overtime. The applied CP current density also influences the coating disbondment. The overall SCC sub-model for coating disbondment is shown in Figure 2.

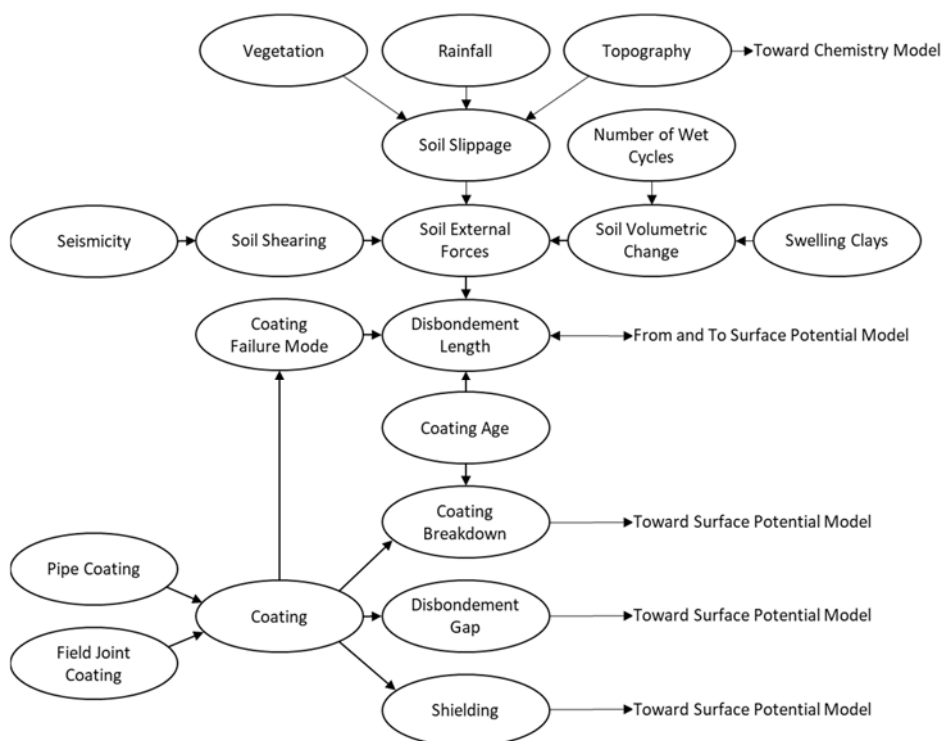


Figure 2: SCC Sub-model for Coating Disbondment

Soil External Forces Effects on Disbondment

The soil around the pipe may damage the coating per three mechanisms: (1) soil expansion or contraction due to the presence of bentonite clay and a change in moisture content, (2) soil slippage due to soil erosion and (3) soil shearing due to earth movements like earthquakes, subsidence, and landslides.

Soil Volumetric Change: Soil swelling and contraction can add sufficient shear stress to cause wrinkling of tape coatings or disbondments in other types of coatings. The swelling depends on the type of clay, the presence of the clay in the unsaturated zone, and the wetting and drying cycles. Detailed finite element analysis of the effect of swelling clays on pipelines have been made [25] and reviews of the effect of clay type on swelling in oil field environments exist [26]. The BN model infers the presence or absence of stresses from clay swelling/contraction. The volumetric changes are mainly influenced by the clay type and wetting/drying cycles.

Soil Slippage: Soil may slip due to erosion and in the process, damage the pipe coating. Soil slippage has been extensively studied [27-30]. Studies show that at low slope angle where pipelines are usually found, the risk slope instability is limited, especially when vegetation is present. Vegetation such as trees (outside the right of way) or simply brushes and/or grass will help stabilize the slope. However, with high rain and slope angle larger than 10°, the risk of slope instability is not negligible.

Soil Shearing: Seismic effects can cause permanent ground deformations, including fault displacements, landslides, and liquefaction. These deformations can cause pipe bending. Seismic effects can also be transient wave propagation along the pipeline. These strain waves can induce longitudinal stresses on the pipelines and can cause pipelines to buckle and fail. The direct effects on pipelines are often termed fragility and mostly modeled empirically from past repairs on failures of pipelines from seismic events. The probability of immediate or direct failure is given by Tsiniadis *et al.* [31] (Eidinger's Guidelines for the seismic evaluation [32] is necessary to solve Tsiniadis's equation).

Coating Disbondment

Since the initial use of coal tar enamel (CTE) and asphalt products, coating technology has evolved to further the design life and enhance performance of pipelines. As with changes in technology across all industries, newer generation products intend to address the shortcomings of those preceding. In the pipeline case, it may be the limited mechanical and thermo-mechanical properties of CTE and asphalt coatings, or the concerns related to cathodic protection shielding and penetration damage associated with polyethylene coating. Newly developed coatings, such as multi-layer fusion bond epoxy and 3-layer polyolefin systems, are not immune to similar concerns. Multilayer coatings, while providing greater mechanical strength and water exclusion from the steel, may contribute to greater CP shielding once water does penetrate a disbonded area. However, these systems are generally considered to offer superior performance to first generation coatings. As such, new construction in today's pipeline market is dominated by fusion bonded epoxy (especially in North America) [33].

Coating Failure Mode: Pipe coating is susceptible to many modes of failures. These modes of failures can be grouped in 5 major categories.

1. **Loss of Adhesion between pipe and 1st layer of the coating:** Many factors could cause loss of adhesion between coating and pipe surface [34, 35]. For example, it may be due to cathodic disbonding: stray currents originating from DC powered traction systems may result in accelerated cathodic disbonding due to the development of high negative potentials on the pipe. Single layer fusion bonded epoxy and 3LPE systems, which have very good adhesive properties, are expected to incur less damage as a result of this mechanism than 1st generation coating systems.
2. **Mechanical Damage:** Coatings can be mechanically damaged during manufacturing, transportation, installation, backfilling and service. This damage may result from mechanical impact, bending stresses, abrasion due to soil stresses, or other means, leading to cracking, gouging and/or disbonding of the coating.

3. Cracking: Hard coatings are prone to cracking. Cracking of coating may result in the formation of a crevice between the disbonded coating and the steel substrate. The disbonded coating may shield CP under the disbonded coating, while at the same time allowing the renewal of oxygen and ground water at the steel's surface, which would lead to continued corrosion at this site.
4. Heat Blistering: Some coatings, like fusion bonded epoxy, may absorb appreciable amounts of water during transportation and storage. If rapidly heated, water cannot escape in a controlled manner, leading to blistering. The result may be even more severe on thin-walled pipes, which tend to heat even more quickly during welding. The use of alternative field joint coatings which do not require the same rapid heating rates can mitigate this risk.
5. Coating degradation over time such as chemical aging or dissolution. All coatings have a service life, over time a coating will age and deteriorate. Soil stress, pipe movement, temperature changes of the pipe, and wet/dry conditions may reduce effective service life.

Disbondment length: Knudsen and Forsgren [34, 36] showed that the growth of the disbonded region has been found to be proportional to the square root of electrolyte cations diffusion coefficient (e.g. Na^+ , K^+ , Cs^+) since these cations increase the alkalinity under the coating from the CP. To use the empirical equation above, it's important to fix boundary conditions. Experts were asked to provide the expected disbondment under various modes of coating failure. The results from the survey of the experts are shown in Table 1. It should be noted that coating disbondment can reach values larger than 4 feet, however for SCC evaluation, the main effect of the length of the disbondment is shielding which becomes maximal past approximately a z/a ratio of 100, where z is the disbondment length and a is the disbondment gap. For tape coatings where the gap can be as large as 1 cm, the length of disbondment where the potential reaches the OCP asymptotically will be approximately 100 cm. It should be noted that if there is flow of water through the disbonded area, as it can occur when there are two holidays in a spiral wound disbonded region, the asymptotic disbondment length can be longer, However, this is not considered in this model.

Table 1: Disbondment Size as a Function of Coating Failure Mode and External Conditions

	Expected Disbondment Size		Disbondment Size Under Bad Conditions	
	min	max	min	max
Disbondment due to loss of adhesion	0 inch	24 inch	12 inch	48 inch
Penetration through system to steel due to mechanical damage	0 inch	2 inch	1 inch	4 inch
Cracking of topcoat through to steel	0 inch	24 inch	12 inch	48 inch
Coating degradation (chemical aging or dissolution)	0 inch	12 inch	12 inch	48 inch
Blistering or bubbling	0 inch	1 inch	0.5 inch	2 inch

Other parameters have been known to have an effect on the amount of disbondment such as temperature, coating adhesion strength, water chemistry [34]. These parameters are not considered here for simplicity reasons.

Disbondment height: Disbondment height, also called disbondment gap has a strong effect on the chemistry under the disbonded coating, the larger the gap the more water and bicarbonate can accumulate [37]. Also, the wider the gap the more easily cathodic protection can flow in the disbonded region. Coating thicknesses and gap ranges are summarized in Table 2