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MAKING REMAINING LIFE PREDICTIONS FOR POWER CABLES USING RELIABILITY ANALYSES

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ABSTRACT

Most underground cable owners would like to know what the probability is for failure of a given cable asset as a function of material type, function type, age of the asset, geotechnical environment, and other factors, when we know past failure distributions, predominant failure mechanisms, and other attributes. While most underground electric utilities have collected voluminous data that could guide them into better buried cable management in the future, the use of suitable reliability analyses in their asset management programs have been beyond their reach. Often the replacement and rehabilitation decisions have been based on simple rules of thumb rather than either good science or statistical analyses even when tremendous amount of resources and time are expended on benefiting from the use of state-of-the-art cable assessment techniques. When utility engineers struggle to convince the public, shareholders, and the legislators the dire need for increased rate of investments into buried cable assets, it is our obligation to engage the most suitable analytical tools to make the best use of past failure data and available cable infrastructure capex funds. This paper provides a methodology on how sound reliability analysis tools can be used in such management decisions to maintain and operate our underground cables better.

KEYWORDS

Cables, asset management, reliability analyses

INTRODUCTION

Globally we have spent many trillions of dollars into valuable underground cable infrastructure over the past century. We are continuing to spend large budgets on in-situ condition assessment of existing underground cables and on forensic examination. Often, component materials forming these underground assets are also tested resulting in enormous funds being spent for calibration of data collected from other testing techniques, yet little attention has been paid on using proper statistical analyses of all of this data. Most industries outside of cable engineering have progressed much farther in the use of more advanced data analyses over the past 50 years. The most important question to ask ourselves is what is the probability of failure of a given cable as a function of certain attributes such as

- type of component materials in the cable
- type of function?
- age distribution of the asset?
- type of environment?
- break history?
- predominant failure mechanisms?

How do we allocate future funding to get the most optimum return from the current assets, given the limited resources we have for asset management?

STEPS IN RELIABILITY ANALYSES

It is not possible to rely only on the analytical tools known to engineers who have practiced design engineering, condition assessment, and asset management for cables to complete the remaining life predictions. One has to use tools from other industries in performing such reliability studies. The appropriate steps in proper reliability analyses toward remaining life prediction for underground cables shall contain as a minimum:

- Collect and organize track record data.
- Select a statistical distribution that best fits the lifetime data on hand.
- Estimate the defining parameters that fit the statistical distribution chosen to represent the lifetime data, for example using regression studies.
- Make better predictions than rules of thumb on estimates of the life's attributes:

- reliability or representative life of the cable?
- probability of failure for a chosen life span?
- which component material lasts longer?
- under what site and operating conditions?

PROBABILITY DISTRIBUTIONS

The Weibull probability density functions (PDFs) can be used to characterize past failure records of cable or component materials, if sufficient data indicate that one or both of these PDFs would approximate the past failure behavior of the buried assets.

The 3-Parameter Weibull PDF is represented by the following equation:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad (1)$$

Where β is shape parameter
η is scale parameter
γ is location parameter
t is time
f (t) is PDF.

The cumulative distribution function (CDF), F(t), or unreliability function and the reliability function, R(t) can be obtained from f(t) as follows:

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$$F(t) = \int_0^t f(t)\,dt, \text{ and} \quad (2)$$

$$R(t) = 1 - F(t) \quad (3)$$

Weibull failure rate function is given by

$$\lambda(t) = f(t)/R(t) \quad (4)$$

Some observations can be made based on the value of β. For example:

- If $0 < \beta < 1$, there is infant mortality due to either the cables that were installed had defects at the factory, mishandled by the contractor, or the installation and inspection were poor.
- If $\beta = 1$, there are random failures independent of age, and the failure rate does not vary with time.
- If, $\beta > 1$, there are wear-out driven failures primarily due to aging and the rate is increasing with time.

Simpler Weibull PDFs can also be used when the past failure data warrant. The 2-Parameter Weibull Distribution is recommended when the location parameter, γ is set to zero and the 1-Parameter Weibull Distribution, when the shape parameter, β is a constant. In this case, the only unknown is the scale parameter, η. Note that in the formulation of the 1-parameter Weibull PDF, we assume that the shape parameter β is known *a priori* from past experience on either identical or similar underground assets. The unknown parameters that affect the location, scale, and shape are obtained using any one or more of the following techniques:

- Probability plotting
- Rank regression on x
- Rank regression on y
- Maximum likelihood estimation

The most appropriate and even whether one needs a 3-parameter Weibull, is governed by the lifetime data set on hand and good engineering judgment from experience in conducting reliability studies over the years. The normal probability density function can be represented by the form:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (5)$$

where, x is the variable, σ is the standard deviation, and μ is the arithmetic mean. Again, the unreliability function, F(x), reliability function, R(x), and the failure rate function, $\lambda(x)$ for the normal PDF can be written as follows:

$$F(x) = \int_0^x f(x)\,dx, \text{ and} \quad (6)$$

$$R(x) = 1 - F(x) \quad (7)$$

$$\lambda(x) = f(x)/R(x) \quad (8)$$

RESULTS FROM RELIABILITY ANALYSES

The useful results from the above Reliability Analyses are as follows:

- Reliability for a chosen life: what is the likelihood that the XLPE cable in an electric utility district will last at least 50 years?
- Probability of failure for a chosen life: what is the likelihood that the EPR cables owned by the electric utility will last 30 more years?
- Mean life: what is the average life of the city's entire underground cable asset that has certain attributes, for example, buried in low plastic clay (CL) under min 3.6 m (12 ft) of cover in slopes steeper than 6 % in areas that get more than 250 mm (10 inches) of rain per annum with a water table < 1 m (3.28 ft)?
- Failure rate: what is the rate at which the Company A's underground cables will fail during the next 25 years?
- Warranty time: what is the estimated life when the reliability of the cables installed without ducts would either match or exceed electric utility Y's minimum performance goal driven by its budget constraints?

The following additional results could be obtained from the previous reliability analyses:

- Plot of probability of failure over time
- Plot of reliability over time
- Plot of probability density distribution
- Plot of failure rate with time
- Confidence levels to go with the above predictions

THREE CASE HISTORIES

The application of the above techniques for buried pipelines have been applied by the author in a series of projects and samples are shown here to illustrate the power of reliability tools like these for better underground cable management.

Case History 1: **Using Weibull Reliability Analyses**

- City with a population of over 1,000,000.

•The author did a comprehensive assessment of all three transmission pipelines bringing 100% of treated water into the city: structural, geotechnical, hydraulic, seismic, corrosion, and was able to squeeze more out of these to delay capex on a 4th pipeline.

•3,360 km(2,100 miles) of pipe form their distribution system assets with 6,200 breaks over 1977-2002 with pipes going back to 1890s as shown in Table 1.

•They asked for the author's guidance to develop a better asset management system, toward better allocation of their limited funds.

• The results of the 3-parameter Weibull data fit is shown in Figure 1. The results of the Weibull reliability analyses on remaining life for the cast iron and galvanized pipes are shown in Figure 2.

Case History 2: **Using Normal Probability Density Functions**

•PCCP design wall thickness, coating, core, etc. varied
•Depth of cover varied
•Live load varied
•Internal pressure varied
•Level of wall thickness loss due to H2S attack varied
•Wraps of prestress wires varied

Again, proper condition assessment techniques were not used with the evaluation of the pccp present in the force main. Each of these variables were represented by normal PDFs and AWWA C-304 design checks for 66 %, 90%, and 99% confidence levels were made using an excel sheet the author developed. An asset management program based on the results used the following factors:

•Proximity to the river and the level of damage it might engender.
•Amount of concrete core loss due to corrosion
•Relative aggressiveness of native soils
•Surge potential and the working pressure
•Intensity of soil and live loads
•Relative accessibility to the force main

Case History 3: **Using Normal Probability Density Functions**

The author was asked to review the data collected, perform an analysis, and make recommendations for an asset management program after the field data have been collected without his input. Unfortunately, the condition assessment program was not properly designed and the technologies used were not the most suitable. The data collected did not capture all of the past failure patterns. The following summarizes the situation:

•Results of NDT on ductile iron wall thickness along the alignment varied
•Depth of cover varied
•Live load varied
•Internal pressure varied
•Trench condition varied

Each of these were represented by a normal PDF and factors of safety for 66 %, 90%, and 99% confidence levels were predicted to meet AWWA C-150 standards for

•external load induced deflection
•external load induced bending stress
•internal pressure induced hoop tension

to determine which portions of the alignment need to be replaced or relined and the timeline.

CONCLUSIONS

The following conclusions can be made:

1. It is extremely important that cable engineers engage outside the box thinking to improve the delivery to our clients vis-à-vis serving our public better.

2. The engineering tools we use for condition assessment and underground cable management also need to account for past failure records, variability in material properties, construction practices, loads, O&M, site characteristics, etc.

3. It is not possible to obtain a better outcome from our work for our clients, if we keep doing the same thing over and over again. It is absurd for licensed engineers to base their cable management decisions on condition and criticality factors that involve nothing more than a simple addition. Our efforts in underground cable condition assessment and asset management have to include more rigorous statistical evaluations of high quality data.

4. The three case histories presented in this paper using either Weibull or Normal PDFs are steps in the right direction in the use of reliability analyses in underground asset management. Analytical tools such as Markovian models, non-linear programming and dynamic programming techniques, Monte-Carlo simulations, Fuzzy sets, etc. would provide us with even more computational power in our ability to better allocate funding for future underground asset management programs.

5. When asked of Wayne Gretzky about his most important advice to younger players he answered “really simple; always skate to where the puck is likely to be.” It is not possible for us to see ahead clearly without looking back. The pursuits in our asset management work is so similar to playing a game of ice hockey with precision and this takes us back to the advice of Marcus Tellius Cicero during 106 to 43 BC: History is the witness of the times, the light of truth, the life of memory, and the witness of life.

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Table 1 Sample Pipe Break Data

Year	Total Breaks	CI Breaks	Galvanized Breaks
1972	20	16	4
1973	30	24	6
1974	40	32	8
1975	50	40	10
1976	60	48	12
1977	75	60	15
1978	110	88	22
1979	110	88	22
1980	110	88	22
1981	130	104	26
1982	175	140	35
1983	275	220	55
1984	260	208	52
1985	300	240	60
1986	250	200	50
1987	290	232	58
1988	330	264	66
1989	360	288	72
1990	390	312	78
1991	310	248	62
1992	360	288	72
1993	280	224	56
1994	240	192	48
1995	280	224	56
1996	280	224	56
1997	200	160	40
1998	280	224	56
1999	210	168	42
2000	290	232	58
2001	200	160	40
2002	160	128	32

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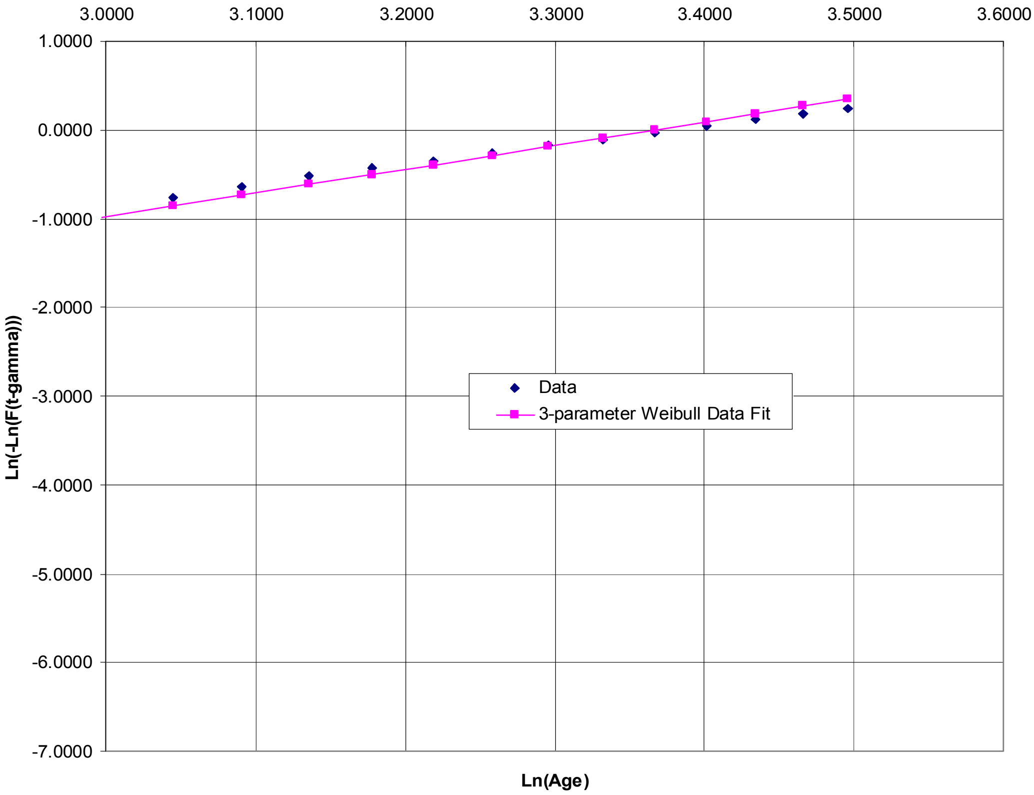

Figure 1: Data Fit for a 3-Parameter Weibull Model

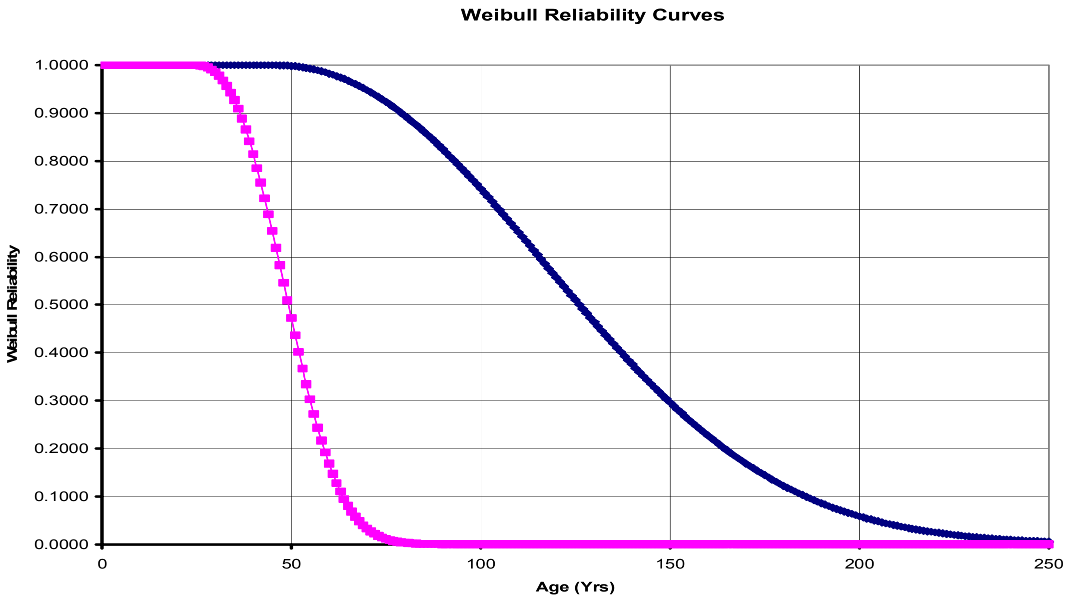

Figure 2: Weibull Reliability Analyses