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A Probabilistic Framework for Prioritizing Wood

Pole Inspections Given Pole Geospatial Data

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***Abstract*—Managing the widely distributed wood pole assets owned by typical electric power utilities in the USA is challeng- ing in the absence of appropriate analytical tools. The traditional method of inspecting poles by headquarters or strictly age is insufficient for effective management since natural hazards cause the largest instantaneous pole replacements. A proba- bilistic framework is developed and presented in this paper to address this issue. Fragility assessment is conducted using Latin hypercube sampling to estimate pole failure probabilities conditional on wind speed intensities. Failure probability esti- mates are obtained using age-dependent fragility functions and appropriate distribution functions for maximum** 3 **s wind gust speeds. Pole locations from an electric power utility’s database management system were imported into ArcMap, a component of Environmental Systems Research Institute geospatial process- ing program. Age distributions were extracted by county and used to estimate expected pole failures. A sort-algorithm on the failures—the inspection order indices gives the proposed appro- priate order of pole locations to be inspected. These calculated values were added as a data layer into ArcMap generating a geospatial visualization of both the orders of pole inspections and probabilistic pole loss estimates for the electric utility by counties. Applying the framework will increase utilities’ visibility into the vulnerability of their pole plants. Emergency prepared- ness will also improve, strengthening customer-perception on utilities’ maintenance efforts.**

***Index Terms*—Aging wood poles, ArcMap, asset management, database** **management,** **failure** **probability,** **geographical**

**information system (GIS), pole inspections, reliability.**

I. INTRODUCTION

FFECTIVE management of electric utility wood poles

is a balance between implementing operations that ensure high pole-reliability and minimizing the cost of those operations. High reliability leads to the prevention of fatalities and damage to structures surrounding the poles, including supported overhead lines that would affect power avail- ability. A wood pole asset manager has to determine an appropriate maintenance schedule. The ideal program would

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preventively replace or reinforce weak poles before they fail in service under typical environmental conditions. Otherwise, replacement costs could be greater than two or three times the cost of preventive replacements, especially in high demand periods like during storms. Thus, the timing of inspections and maintenance operations is important.

A significant number of electric utilities in the U.S. imple- ment a regular pole inspection program. Though they keep records of their wood pole assets, they do not analyze their data since a substantial amount of expertise in complex ana- lytical methods would be required. Instead, utilities rely on inspection companies to understand their pole plant health and design their inspection programs. Traditionally, the inspection company provides the utility with a set of diagnostic tech- niques of varying costs and expected accuracies. The utility makes a selection based on the maintenance budget within the contract period. Diagnostic techniques are used to identify poles that should be replaced or should remain in service based on American National Standards Institute (ANSI) O5.1 stan- dards governing the strength and design of poles [1]. Poles are inspected and maintained accordingly until the end of the inspection cycle or contract. Their records are then updated with the condition assessment results.

Pole maintenance programs in the U.S. and abroad are expensive. Southern California Edison Company recorded spending between $83.8 and $155.3 million per annum on wood pole replacements under capital maintenance pro- grams in 2005–2009 [2]. Yet, condition assessment methods on which these programs rely are sometimes only as accurate as a random guess, making wood pole management decisions very challenging. As of the year 1995, no highly reliable cor- relations between tests and actual bending strength had been found, irrespective of pole age [3]. In 2007, an evaluation of diagnostic tests conducted on a small sample of wood poles by the National Electric Energy Testing Research and Application Center still showed low correlations and accuracies. The com- plexity of strength-prediction (and moduli of rupture) is largely because of the biological nature of wood poles: they have vary- ing properties even within the same class (same height and ground-line circumference). Though general inaccuracy is low, test specificities have been found to be high in general. That is, the techniques rarely recommend the replacement of a strong pole. However, sensitivities are low (the ability to detect poles that are below ANSI standards on strength). In other words, several poles that will fail are left in service even with main- tenance programs. Without expertise in complex analytical

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procedures to assess vulnerability or improve their mainte- nance expenditure decisions, utilities will continue to waste money in misclassification costs. A proper solution to asset management will reduce these costs and apply test specificity- sensitivity information in designing a maintenance program.

It is a common practice to inspect the oldest regions of pole service in the first year of an inspection program. The use of age as the sole factor that determines inspection-order is an incomplete strategy for the following reasons. Bulk replace- ments of failed poles have historically not been a function of age but weather hazards. Also, weather conditions appear to be worsening over the years so that even young poles in high wind regions may be more likely to fail than old poles in low wind regions. Thus, at the least, a combination of pole age, fragility, and weather hazard data should drive deci- sions on the order with which zones of pole locations are inspected.

Zoning approaches have been applied in different research fields for deriving maps that depict damage intensities based on probabilistic assessments of hazards. A methodology for developing a probabilistic seismic ground motion map of Canada was presented in [4] for visualization of lev- els of seismic ground motion in the region. Researchers Lo and Jean in [5] presented a similar map for the Taiwan region. A system of models is presented in [6] for calculating tree damage probability under high winds within a land- scape using geographical information systems (GIS) for zonal computations. A similar procedure for categorizing probabilis- tic failure risk of wood poles using hurricane hazards, for instance, would be beneficial to wood pole asset managers.

This paper presents a stochastic framework for prioritiz- ing the inspection of aging power utility wood poles by zones using fragility assessment methodologies. The fragility assess- ment applied here is as demonstrated in [7], where the hazard of interest is strong winds or hurricanes. The indicator that will be assigned to each zone, called the inspection order index (IOI), relies on the calculated age-dependent fragility curves and pole age distributions. It is a measure of pole fail- ure risk under wind hazards. In addition to provide a sequence for cyclic inspections, the index will serve as guidance for selecting diagnostic technique options and determining main- tenance actions from condition assessment recommendations. An illustration of the method on a real electric utility pole plant is provided. A generalized extreme value distribution is used to describe the probability of maximum wind speeds in this paper, as it provided the best fit to hurricane data for the simulated region. The IOI approach differs from the popu- lar methodologies for wood pole management in that it does not rely solely on time data as in [8], which uses a lifetime data analysis approach or [9] where probability functions of pole strength and climatic loads are utilized neglecting age. The developed framework is useful for aging power system assets vulnerable to natural hazards.

II. POLE PLANT GEOSPATIAL DATABASES

Wood pole inspection databases contain pole attributes

like pole class, species, ground-line circumference, year

TABLE I

A FEW ATTRIBUTES (COLUMN TITLES) IN A REAL ELECTRIC POWER

UTILITY WOOD POLE INSPECTION DATABASE SHOWING HYPOTHETICAL POLE DATA

of manufacture, identification information like ID number, manufacturing company, location of pole (*x*-coordinate and *y*-coordinate), and data on condition assessment: ground-line circumference of the pole at the time of inspection, treatment applied to the pole during inspection, recommended main- tenance action to be taken on the pole, to mention a few. Microsoft Access is the popular database management system used by electric power utilities for storing pole attributes. An illustration of a wood pole inspection database table is shown in Table I. These databases are typically not reused or further analyzed by the power utilities but are stored and used for data retrieval whenever necessary.

Recently, power utilities started increasing use of the geographical information for asset management, migrating data into GISs. Around 2009, Gulf Power of the Southern Company distribution GIS (DistGIS) transitioned to a DistGIS, with a similar move for the transmission system. In 2008, Osmose Utilities Services Inc., a leading maintenance and inspection service provider to electric utilities, launched a mapping solution called online data to facilitate access to survey and asset inspection data by geographical features. The availability of the poles and assets in GIS databases allows for visualization of asset locations for more reasons than asset management including maintenance planning, network planning, and outage management. Asset managers utilize maintenance codes from the inspection databases to deter- mine actions to take on the wood poles inspected annually. Meanwhile, contracted inspection companies use the databases to determine regions to inspect in each following inspection year, assuming that inspection schedules are regular.

At the beginning of each inspection cycle, regions with the oldest wood poles are given priority inspection. However, most poles fail in reaction to external forces like vehicu- lar accidents, wind or ice storms, hurricanes, and tornadoes. Outside of these forces, poles could be in service longer than 100 years, as fragility assessment results and pole records show: the probability of failure of 100-year old poles or older for wind speeds less than 100 mi/h is less than one (1). The probability of failure of a new pole at higher speeds, like 125 mi/h, a Category three hurricane by the Saffir–Simpson scale, is greater than zero (0). That is, it could fail. Thus, using age and wind hazard information is more appropriate for decision-making on inspections than using age data alone. The developed probabilistic framework is presented here.

III. IOI

The failure of aging wood poles to remain in service (not break) in the event of a hurricane is an uncertain event,

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stemming from uncertainty in the hurricane demand on the form with a cumulative distribution function of the form

pole and the uncertainty in the pole capacity. Pole fragility curves relate probability of failure to the intensity of wind hazards. Using classical reliability theory terms, the failure

*F* (*y*) = exp − 1 + ξ

*y* − μ

σ

~~−~~1 ξ

(4)

event is characterized by a limit state function *H(X)*, where *X* is a set of random variables that contribute to the limit state of the system of wood poles. The system is said to have failed to meet performance criteria when *H(X)* < 0. Using the law of total probability, the probability of failure *Pf* is simply defined as

which is defined on the set {*y*:1+ξ(*y*−μ)/σ > 0}, where with μ(−∞ < μ < ∞) is the location parameter, σ(σ > ∞) is the scale parameter and ξ(−∞ < ξ < ∞) is the shape parameter. In this parameterization, the Type I class of extreme value distributions can be derived from (4) by approaching ξ to zero, while Types II and III distributions are derived, respectively

*Pf* = *P* [*H* (*X*) < 0] =

*y*

*P H* (*X*) < 0|IM = *y f*IM (*y*) dy

(1)

ξ > 0 and ξ < 0 cases. Through this unification and by inference on ξ , the most appropriate form of tail behavior will be determined by the data rather than through subjective *a priori* judgments about the type of the individual extreme

where IM stands for the intensity measure, which is a random variable that describes the intensity of the applied demand;

*P*[*H*(*X*) < 0|IM = *y*] is called the fragility function, which basically provides the conditional probability of failure given

IM = *y*; and finally *f* IM*(y)* defines the probability density function (pdf) of the intensity measure of the hazard.

Applying structural reliability principles, the failure of poles to remain in service and not break under hurricane conditions is based on the wind demand on the poles exceeding their capacity limit. Denoting the demand by the random variable *D*,

and the capacity by *C*, *H(X)* is simply defined as *C* − *D*, in which *C* and *D* may be both either deformation or strength quantities. The damage state of interest is the breakage of the utility poles, simply evaluated by comparing the maximum induced moment demand from lateral wind pressure to the moment capacity of the pole. In terms of *C* and *D*, including the time dependency of the model, where *T* is the age of a wood pole taken as a random variable

*Pf* (*t*) = *P* [*H* (*X*) < 0|*T* = *t*]

= *y P C* < *D*|IM = *y*, *T* = *t f*IM(*y*) dy. (2)

The density functions that characterize *C*, *D*, and even the pdf, *f* IM*(y)*, may vary per zone in a state served by an electric power utility. Wind hazard data for 10, 20, 50, 100, 200, 500, and 1000 years return periods can be derived for different counties in a state from Hazards U.S. (HAZUS), a GIS-based natural hazard loss estimation software package. These return periods and associated wind speeds can provide information regarding the probability distribution of maximum 3 s wind gust speeds for each of the counties. The probability of wind speed not exceeding a particular limit is related to the return period *T* associated with that limit speed in the following form:

value family to adopt.

Fragility assessment approaches and wind hazard models have not been used in conjunction with aging and geospatial data for wood pole management decisions. Yet, they present a very useful application. The framework is developed here. The expected number of wood pole failures in zone *j* given the age distribution *N(t)* of poles in that zone is defined in (5) as the zonal IOI*j*

IOI*j* = *Pf* (*t*)*j* × *Nj*(*t*) (5)

*t*

where the multiplicand is the probability of a failure of a wood pole of age *t* in zone *j* from (2) and the multiplier is the age distribution of wood poles in zone *j*. In this paper, counties are the defining zones so that IOI*j* is computed using wind demands and age distributions in each county of a state served by an electric power utility. This index has been developed to aid with decision-making on pole inspections. However, it can be used for other applications as will be discussed later in this paper. We assume that the maximum wind speeds are uniform within each county and use the maximum speeds in the center of the counties.

*A. GIS Database Layering*

The layers of data from an electric power utility’s wood pole GIS relevant for processing the zonal IOIs are pole attribute layer, soil moisture layer, environmental moisture layer, and wind hazard layer. The pole attribute layer con- sists of year of manufacture, pole class, pole species, initial treatment data, and location (*x*-coordinate and *y*-coordinate) data from the inspection databases. The moisture data can be obtained from the National Climatic Data Center of National Oceanic and Atmospheric Administration. Wind hazard data is from HAZUS, and forms another layer of information in a geo-

*F*IM(*y* = *VT* ) = *P*(*Y* ≤ *y*) = 1 − *T*1 .

(3)

database. The year of manufacture provides the age of wood poles to determine age distribution in a given geographical region. Pole class, species, and initial treatment information

Weibull, lognormal, and generalized extreme value distri- butions are possible distributions used to represent probability distribution of the maximum wind speeds in literature. The generalized extreme value distribution, for instance, combines original families of extreme value distributions i.e., Gumbel (Type I), Frechet (Type II), and Weibull (Type III) into one

are used for estimating the distribution of pole capacities for fragility assessment. The moisture and treatment informa- tion can be used to determine deterioration and decay of the poles for the time-dependent factor in fragility assessment. The wind hazard is used to estimate the distribution of poten- tial wind demand on wood poles per region and *f* IM(*y*), the

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TABLE II

RANKING (AND ORDER STATISTICS) OF ZONES BY IOI

Fig. 1. Age and historical wind or hurricane layers of an electric power

utility wood pole GIS database and HAZUS database showing Regions 1–3, with maximum wind speeds per zone *wj* and average ages *aj* displayed. An IOI is calculated per zone as IOI*j*.

**Algorithm 1** Compute\_IOIj (m, N, f, P)

// Problem description: This algorithm is for computing the

IOI for wood // poles per zone given n zones

// Input : **m** zones, an array of the number of poles **N** per

age in each zone, wind hazard pdf **f** per zone and a

time-dependent fragility function for all wind speeds **P**

// Output: The IOI for each zone j

**for** j ← 1 to m **do**

{F*j* [t] ← *y* **P** × **fj** dy

IOI [j] ← t F*j* [t] × **Nj**[t]

j ← j + 1}

pdf of the intensity measure of the hazard. An illustration of the geographical information showing two key layers of the data used in calculating IOI*j* is given in Fig. 1. The maximum wind speeds *wj* in the center of the zone/district and averages of the age in the zones *aj* are displayed in the figure.

In its discrete form, the summation over all ages in zone *j*, of the product of the expected failure probabilities per age *t Pf (t)j*, and the age distributions extracted from a GIS, gives IOI*j*.

*B. Algorithm for Computing IOI*

The algorithm for computing the IOI for each zone in the

state is provided in Algorithm 1.

*C. Sorting the Indices*

The indices are ranked in descending order to determine the sequence of wood pole inspections in the zones served by an electric power utility. The zone with the highest rank implies one with the worst failure risk while that with the lowest rank is the one with the lowest failure risk. The highest ranking zone must be inspected first and the least last. Sort algorithms are common in the literature.

*D. Diagnostic Selection and Maintenance Decisions by Zone*

Diagnostic techniques applied in assessing the condition of in-service wood poles are largely inaccurate as previously mentioned. However, small sample tests showed high speci- ficities *s*1. This means that there are rarely false positives or wood poles marked for replacement that were not below ANSI

standards. The techniques, however, rank poorly in detecting

below-standard poles: low sensitivity *s*2.

Knowledge of the statistics should be used to improve decision-making on planned maintenance actions given the sorted indices. In high risk zones (high IOIs), in addition to poles identified for replacement *c*, nonpriority rejects *r* should be scheduled for reinforcement with steel using a multiplica-

tive factor *mn* of (*1/s*2 − 1) times the number of priority reject-poles at the minimum [see (6)]. This compensates for the weak poles not detected by the diagnostic techniques and would reduce the likelihood and number of misclassified poles failing in the event of a typical hurricane in the region

1

*r* = *c* × *mn* = *c* × *s*2 − 1 (6)

where *r* is the number of nonpriority reject-poles to be rein- forced, *c* is the number of priority-reject poles scheduled for immediate replacement, *mn* is a multiplicative factor, and *s*2 is the known sensitivity of a diagnostic test.

Conversely, in very low risk zones (low IOIs), additional reinforcement or replacements need not be performed. Only the number identified for replacement should be replaced pre- ventively in that year. Visual inspections or other less intrusive and inexpensive techniques may be used in these low-risk regions.

A table of developed decision-guidelines showing

a sequence of zonal inspections is given in Table II. Diagnostic options offered by an inspection company are also shown with the multiplicative factor of maintenance actions to compensate for false negatives (below-standard poles misclassified during inspections). In the table, Option *X* may be an expensive option while *A* is inexpensive and nonintrusive.

Actual selection of diagnostic technique and choice of mul- tiplicative factor should depend on IOI thresholds that signify substantial risk to emergency asset replacement funding or human safety. Thresholds are not yet available. Further work is required to obtain them. In structural engineering applications, return period statistics of hazards are used to set acceptable damage states. This concept could be applied here. Another option would be to use economic analysis results from IOIs to determine such thresholds. A thorough optimum maintenance program will determine appropriate values for *m*1 through *mN* , IOI thresholds, and an inspection cycle as choice variables to obtain the minimum annual or lifecycle cost of wood poles including costs of misclassification. By comparing to the tra- ditional program, net savings resulting from the use of the IOI

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Fig. 3. Errors in fitted probability distributions. Root-mean-square error

in (a) probabilities and (b) wind speeds.

Fig. 2. Collage of images showing few locations of class 5 wood poles (solid circles) owned by utility A in a state. Class 5 poles are densely populated in some regions and sparse in others. Map of entire region served by utility A is obscured to protect privacy of the electric utility.

for decision-making can be found. This will be accomplished in future work.

IV. ILLUSTRATION: REAL-UTILITY DATABASE

For privacy purposes, the utility whose data has been analyzed for illustration of this paper will be identified as “utility A.” Like other electric power utilities, utility A stores its pole records and attributes in MS Access databases, with several columns of attributes per wood pole. A database containing a subset of previously inspected wood poles in the electric utility was presented for analysis. In this paper, age-dependent fragility curves of class 5 southern pine wood poles were generated using Latin hypercube sampling. To be consistent with the fragility analysis, the same class, and species of poles are used here.

A query was run in MS Access to extract data on latitudes and longitudes of pole locations, year of manufacture of poles, pole class, and pole species, most importantly. The criteria for pole class and species were set to be class 5 and southern pine, respectively. The query resulted in over 380000 poles.

A pole location layer for the subset was generated in ArcView, a full-featured GIS program, using the latitude and longitude information from the query-table. An additional field for pole age was defined in the attribute table of the dataset in ArcView, which was calculated from the “year of manufacture” attribute in the query-table. By joining this new data layer with a layer containing polygons of counties in the state where utility A is located, the pole ages corresponding to each county were obtained. The join-output was further pro- cessed in MS Excel. The data summarization tool, PivotTable in MS Excel was used to group the pole ages by counties in preparation for computation of the IOI. A map of a few of the poles is shown in Fig. 2.

Fig. 4. Collage showing color intensities in a few regions served by utility

A. The corresponding IOI representing the expected number of failures under maximum 3 s wind gust speeds for those areas given the population and ages of the class 5 poles, are shown. Map of entire region served by utility A is obscured to protect privacy of the electric utility.

Wind hazard data for 10, 20, 50, 100, 200, 500, and 1000 years return periods were derived from the wind hazard layer in HAZUS for each of the counties in the state. These return periods and associated wind speeds provide informa- tion regarding the probability distribution of maximum 3 s wind gust speeds for each of the counties. The probability of maximum wind speeds in the counties was determined. The speeds were fit to Weibull, lognormal, and general- ized extreme value distributions. This paper implements the generalized extreme value distribution to represent the prob- ability distribution of the maximum wind speeds at county levels.

A least squares approach was used to fit the cumulative distribution functions of Weibull, lognormal, and generalized extreme value distributions to the complements of proba- bilities of exceedance and corresponding wind speeds. This approach will result in best fits and distribution parame- ters for the models for each of the counties. The errors in the fits for the three distributions and for each county are shown in Fig. 3. It appears that the errors associated with generalized extreme value distributions are considerably smaller than those for Weibull and lognormal distributions. For this reason, the generalized extreme value distribution was selected.

By integrating the products of the fragility curves for each age of wood poles and the probability distributions of the maximum wind speeds per county, the probabilities of failure

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of each age of wood pole in the respective counties were obtained.

Implementing the algorithm of the IOI, that is, in its discrete form, a summation of the product of the failure probabilities and the age distributions of the poles per county, the respective indices were obtained.

Performing a sort algorithm on the indices for the subset of poles used in this illustration showed that the most at-risk county was expected to experience failures of 1240 poles. On the other hand, six other counties would see failures less than 10. About 35% of the counties showed low likeli- hoods of experiencing class 5 pole failures, either because they had no poles (and therefore no data) or the maximum wind speeds are low in those regions. The map of zones showing concentration gradients for the IOI is provided in Fig. 4. Based on the results, the most stringent (and consequently the most expensive) methods of pole inspection should be applied to the county with 1240 expected failures. The power utility may also expect to allocate the highest capital/maintenance expen- diture in that county for class 5 poles relative to the other counties.

V. CONCLUSION

This paper shows an advanced application of GIS in wood pole asset management relative to traditional and negligible use of pole geospatial records by the electric power utility. It has been shown that the framework could provide a useful, logical sequence for inspecting wood poles owned by electric power utilities. Unlike power system reliability indices (cus- tomer average interruption frequency Index, system average interruption frequency index etc.) that are applied toward eval- uation of electric utilities, the IOI is designed to be a zonal assessment tool to probabilistically identify high failure risk zones during storms. Thus, the IOI also serves as a predictive tool for estimating the expected number of wood poles that will fail under a hurricane given the geographical locations of the poles.

Wood pole failure prediction per zone will be improved as more relevant variables affecting pole capacity are incor- porated into the age-dependent pole fragility assessment calculations. This tool would be beneficial to electric utili- ties and inspection companies alike, as a guide for inspections and planning emergency management procedures and bud- gets resulting from natural hazards like hurricanes. As more smartness is incorporated into electric power utility asset man- agement, asset databases may become automatically (rather than manually) updated, further enhancing decision-making tools like the IOI. The developed probabilistic framework can be applied to other power system assets of similarly large scale as wood poles that are widely distributed in geography and are affected by natural hazards.

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