Systematic Evaluation of Structural Deterioration in Underwater Bridge Substructures

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A comprehensive statistical analysis was performed on the condition data generated by a statewide underwater inspection of bridges in Louisiana. The research defined pertinent underwater structural decay characteristics and established a method for determining a bridge's propensity for underwater deterioration on the basis of those relevant factors. The inspection results were reviewed to ascertain the impact of human bias on consistency in the bridge condition ratings. Using a set of importance factors obtained through a questionnaire submitted to a group of inspectors, the fuzzy set theory was employed to assist in the removal of data incongruities. A combination of pure fuzzy set theory and classical binary weighing was found to produce optimal results. Bridge age, material type, and location were found to be significant in defining the rate of deterioration in Louisiana bridges. Linear least-squares, piecewise linear least-squares, and polynomial regression curves were matched to the overall underwater condition ratings. Comparisons of regression curves for neighboring states indicated reasonable consistency in results for differential inspection programs if similar inspection methodologies are employed. The correlation between above-water and subsurface inspection ratings was found to be poor for concrete and steel bent bridges but acceptable for timber bent bridges within a given age group. Additionally, a poor correlation was found between water quality data and underwater bridge deterioration rates. A methodology for determining the frequency and detail of future underwater inspection projects was developed on the basis of the deterioration trends and available bridge decay-defining characteristics discovered in this research.

With over half of the United States' 600,000 bridges now over 50 years old, there is growing interest in discovering new and more efficient methods for maintaining and rehabilitating the existing bridge network at the least possible cost. Performance prediction curves based on archived bridge inspection data traditionally have provided graphic evidence of the behavior of a system of bridges. The performance curves allow transportation officials to comparatively examine each bridge to find those structures that show regression rates that are significantly greater than expected. The engineer may then choose to grant priority for future inspections to any bridge that shows a propensity for unusually high deterioration, thus assuring that the structure does not unexpectedly enter a critical condition state. Traditionally, scheduling of future inspections has relied on an informal decision-making process that is based on the experience of the bridge maintenance engineer. Today, the popularity of computerized bridge inspection data storage and retrieval allows greater optimization in scheduling future inspections.

The purpose of this paper is to introduce a procedure for assigning an inspection priority value for a given bridge element on the basis of the element's past conditional behavior and other decay-defining parameters. The methodology will be illustrated by a study of pile bents taken from the data of a statewide underwater bridge inspection program initiated in 1991 in Louisiana.

DATA SET DEVELOPMENT

In 1991 and 1992, the Louisiana Department of Transportation and Development (LDOTD) initiated its first statewide underwater inspection of bridge structures. Divers were required to subjectively rate each of 10 to 19 items (depending on material type) for every bent, pier, and abutment of over 600 bridges across the state as well as to give an overall bent or pier rating. The condition ratings for these items ranged from 1 to 7 and were based on a list of descriptive guidelines listed by Avent and Whitmer (*1*).

Numbering over 2,400, bridge bents constituted the largest type of structure investigated in the Louisiana inspection program. Additionally, bents with imperfect ratings for scour and erosion were excluded from the data base because the presence of these conditions would have influenced the assessment of the condition of the element itself. The remaining 2,200 bents served as the source for the material degradation relationships described in this paper.

The most important rating was the overall underwater condition rating (OVR), a single value representing the general condition of the bent that was based on the individual ratings. Because divers may consider the importance of each of the items differently when casually formulating an OVR in their minds, this method of assigning the OVR is inconsistent. Because the OVR is the most important single indicator of the condition of the structural element, the lack of consistency in determining the OVR hinders any comparative analysis within the set of underwater bridge condition appraisals. This obstacle was overcome by employing a factoring routine that computes the element's OVR using a weighted average for each of the important values of the element's 10 to 19 observations. In this study, a group of ten inspectors and experienced engineers were surveyed to determine the relative importance each of the 10 to 19 items should be allotted when formulating the element's OVR.

One-to-one comparisons of the field-assigned overall ratings (OVRs) and the corresponding computer-generated factored overall condition ratios (FOVRs) showed a general agreement between the values for the bent population. Summary statistics indicate comparable mean values (6.12 versus 6.21) and standard deviations (0.82 versus 0.94) for the OVRs and FOVRs, respectively. Only

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seven of the bridge elements (0.3 percent of the data set) were found to have differences greater than one-half point between the OVRs and the FOVRs.

FACTORS INFLUENCING UNDERWATER DECAY

Because the underwater portions of a bridge structure typically do not receive periodic maintenance, the condition can be assumed to regress (and never improve) from the date of construction. Thus, the average rate of underwater decay can be defined as

$$ADR = 7 - \frac{FOVR}{T} \tag{1}$$

where

ADR = average annual deterioration rate,
$FOVR$ = factored overall underwater condition rating on a seven-point scale, and
T = bridge age in years.

To predict the behavior of a structure, the conditions that influence the ADR must be identified and investigated for their contribution to the structure's rate of decay. From the list of available data and descriptive parameters for each bent, the average daily traffic (ADT), climate region (local environmental effects), and material type were thought to be potentially significant factors in describing the ADR of a given bent in Louisiana. An analysis of variance (ANOVA) was performed on each of these factors to numerically assess the significance of the factor at a 95 percent confidence level.

The ANOVA performed to study the effects of ADT on the regression rate was conducted using the continuous relationship described by the third-order polynomial curve:

$$QVR\ (T_i{\cdot}A_i) = \beta_0 + \beta_1 T_i A_i + \beta_2 T_i A_i^2 + \beta_3 T_i A_i^3 + \epsilon_i \tag{2}$$

where $FOVR(T_i,A_i)$ is the factored overall condition rating of bent I as a function of the bent age (T_i) and the ADT carried by the bent (A_i). The beta values (β_0, β_1, β_2, β_3) are constants generated when the equation is fitted to the data, and ϵ_i is the term describing the error between the equation and the actual FOVR for bent I.

From the results indicated in Table 1, the effect of ADT on the rate of change in the FOVR is insignificant for each of the terms of the polynomial at the 95 percent confidence level, as witnessed by the P-values greater than 0.05.

In processing the ANOVA of the influence of climate region on the rate of regression in the overall underwater condition, the definition of the climate region itself proved a difficult task. Generally speaking, Louisiana is climatically homogeneous; however there are small differences in weather and terrain between the northern and southern portions of the state defined by a line of latitude running through Alexandria. An ANOVA processed to investigate the influence of this two-region climate zone on the ADR indicated that the climate was an insignificant factor with a P-value = 0.109. However, reprocessing the model with nine regional climate zones (in which each region is identically the same as the LDOTD district in which the bent was located) improved the P-value to 0.068.

Further detailed analysis revealed that, although southern Louisiana bents had marginally greater ADRs compared with northern Louisiana bents (20 percent higher in the north), those bents located along the Gulf Coast were witnessing regression rates up to 60 percent greater than the remaining bent population in the same southern district. Table 2 details the ADRs of item observations for concrete bents in a region located in a particular southwestern Louisiana region in which saltwater intrusion has been measured several miles inland from the coast.

Finally, the material of construction was investigated as a potential factor in describing the propensity for underwater decay. An ANOVA performed on a categorical model relating the material type (concrete, steel, or timber) to the ADR produced a P-value = 0.001, a value that is highly significant at a confidence level of 95 percent. The high level of significance results both from the superiority in underwater performance of one material over another and variations in the depth and type of observations recorded for bents of different material types. In light of the significance of the material of construction in determining the propensity for decay, material type must be considered when determining the bent's conditional regression characteristics.

CORRELATION OF ABOVE SURFACE AND SUBSURFACE EVALUATIONS

According to LDOTD guidelines for determining the frequency of underwater inspections, every bridge in the state that crosses rivers over 4 ft deep must undergo an underwater inspection once every 5 years and more frequently if conditions indicate a potential underwater problem. Following similar FHWA criteria, every bridge in the state undergoes a routine above-surface inspection at least once every 2 years. During these biennial surveys, the condition of the bridge substructure (at least those portions visible from above the surface of the water) are rated on a nine-point scale. The possibility

TABLE 1 ADR ANOVA Data Summary Table

Factor	Factor Definition	P-Value
Average Daily Traffic:		
Factor 1	Ti * (Ai)	0.278
Factor 2	Ti * (Ai)^2	0.091
Factor 3	Ti * (Ai)^3	0.054
Climate Zone:		
Two Regions	North/South La.	0.109
Nine Regions	Region = DOT Dist. #	0.068
Material Type:	Concrete/Steel/Timber	0.001

TABLE 2 Coastal Effects on ADRs for Southwestern Louisiana

Item Rated	ADR X 1000	
	SW La. Coastal Region	All SW La.
Cracks	6.053	5.544
Spalls	27.78	17.36
Exposed Reinforced Concrete	0.0	0.0
Laitance	0.0	0.0
Sulphate Attack	0.0	0.0
Honeycombing	[0.355]	[0.273]
Rustspots	14.21	9.411
Grout Loss	62.50	41.90

Bracketed values indicate less than 5 percent (5%) of the bents within the region were assessed at a rating less than 7 (new) for that item. Zero (0.0) values indicate all bents within the region had ratings of 7 for that item.

that the above-surface substructural rating (SSR) might predict the underwater condition (FOVR) was investigated using a Pearson product-moment correlation analysis, the results of which are given in Table 3.

The greatest degree of correlation between the SSR and FOVR for a given bent is found for bent elements constructed of timber. For these structures the Pearson product-moment coefficient (ρ) ranged from $0.746 < \rho < 0.877$ across all the age groups ($\rho = 1$ indicates linear correlation). In contrast, steel and concrete bents could not generate a ρ-coefficient greater than 0.5 for any age group. The high degree of correlation between the SSR and FOVR for timber bents is likely the result of two characteristics of timber structures: first, timber bridges generally cross smaller, shallower, slow-moving rivers or bayous where much of the substructure is above the water surface and, second, timber piles will generally exhibit the greatest amount of deterioration at or just above the water surface. In this area (easily seen from above the surface) repeated cycles of wetting and drying have been proven to accelerate the mechanisms of timber decay (2). Consequently, for timber bents, the SSR may serve as an indicator of the underwater condition.

METHODOLOGY FOR NUMERICALLY DEFINING INSPECTION PRIORITIES

Although the National Bridge Inspection Standards require that all bridges with at least part of their structure located in water receive periodic inspections of those submerged elements, there exists no federal requirement that precisely dictates the frequency and level of underwater inspection, as long as each applicable structure is routinely investigated at least once every 5 years (3). FHWA recommends that nonscheduled inspections, that is, inspections more frequent than once every 5 years, should be conducted on the basis of the local transportation officials' assessment of certain known conditions, including incidence of flooding, debris build-up, vessel impact, and bridge importance within the system (3). However, for any given bridge system, a prioritization of the underwater inspections for the system elements can be numerically established by considering all applicable factors and applying the numerical assessment of those factors to each element.

Before summation, however, the factors should be weighted by a value indicative of the degree of correlation between each individual factor and the anticipated rate of underwater deterioration attributable to that factor. The relationship is simply the summation of weighted terms and, using the terminology of bridge inspection, is hereby proposed to be described by the basic mathematical operation

$$P_e = \sum_{m=1}^{n} C_m * R_{m,e} \tag{3}$$

where

P_e = inspection priority ranking for element e;
C_m = weighting value for factor m; and
$R_{m,e}$ = assessment or rating for factor m of a total of n factors, for element e.

Not all bridges will be subject to the same rating factors because those rating factors are dependent on such characteristics as material type. Normalization of Equation 3 is necessary for comparison

TABLE 3 Pearson Product-Moment Coefficients for SSR-to-FOVR Correlations

Age Group (years)	All Materials	Concrete	Steel	Timber
[0 to 20]	0.151	0.285	0.720	0.746
[20 to 40]	0.396	0.436	[-][1]	0.858
[40 to 60]	0.229	0.270	[-][1]	0.783
[60 to 80]	0.360	0.325	[-][1]	0.877

1: Insufficient data to establish correlation.

across categorical boundaries. Thus, the prioritization ranking process proposed in Equation 3 becomes

$$P_e = \sum_{m=1}^{n} \frac{C_m * R_{m,e}}{(C_m)_{\max} * (R_{m,e})_{\max}} \tag{4}$$

for all applicable ratings m for the given element,

where

$(C_m)_{\max}$ = maximum weighting coefficient for each factor m of n factors; and
$(R_{m,e})_{\max}$ = the maximum assessment or rating for each factor m of element e.

The value of the rating matrix, $R_{m,e}$, may be extracted from inspection data or other sources supplying element particular condition information and may be either continuous or categorical in nature. Evaluation of the weighting factor C_m might be dependent on an elemental categorical definition, and the rating scale may be peculiar to a given observation or measurement as well. For example, the correlation of decay to a geographical factor may be different for steel or concrete bents on the basis of past experiences; hence the weight given to that factor may be dependent on the material-type category.

Some factors apply to all elements of a given type or location. For subcategorical weighting and the application of these broad-based factors, Equation 4 may be modified to include one or more general beta-weighting factors:

$$P_e = \sum_{m=1}^{n} \frac{C_m * R_{m,e}}{(C_m)_{\max} * (R_{m,e})_{\max}} * \beta_1 * \beta_2 \ldots \tag{5}$$

where β_1, β_2, and soon are the subcategorical weights or general factors.

The development of an inspection priority algorithm will generally involve two basic steps. First, the factors that may drive the frequency and level of inspection must be determined, and the available $R_{m,e}$ values must be collected; second, the weighting factors, C_m, associated with the $R_{m,e}$ values must be assembled. For calculating the underwater inspection priority for Louisiana bents, the list of physical parameters and ratings to be considered included bent age, material type (concrete, steel, timber), structure type (bent, pier, etc.), overall underwater condition rating (FOVR), subcomponent ratings (i.e., the ratings given to the items that contribute to the FOVR), location (latitude and longitude), above-water assigned substructural rating, and the criticality of the element to bridge network, listed by LDOTD as "state priority points." These terms can be simply extracted from the LDOTD data base for each bridge and, with the exception of the criticality factor, are known to influence conditional regression.

The C_m factors are not necessarily constants; instead, they take on a predetermined value, depending on the interpretation of its associated $R_{m,e}$ term. For example, although age is of high importance in establishing a propensity for deterioration, it has been shown that the typical regression of concrete bents in Louisiana is not constant over the bent's lifespan. Consequently, the priority for conducting underwater inspections, as well as the level of the inspections themselves, should optimally be indexed in some manner to the age of the structure. In effect, the weighting matrix will be populated by a collection of functions that establish a particular R_e (the ratings assigned to a given element e) contribution to the overall priority rating, P_e, based on the relative value of R_e. It can be seen, then, that each rating term has a general categorical importance as well as a particular significance based on the magnitude of the term.

To differentiate the importance of a factor with the significance of the value assigned to that particular factor, it will be beneficial to consider the weighting value as the product of two weights: (*a*) the importance weight (I_m); and (*b*) the value significance weight (S_m). This operation will allow the weight allotted to any rating value used to establish the structure's inspection priority to be a function of both the general importance of that factor in determining the rate of underwater deterioration and the relative magnitude of that particular value.

Modifying Equation 5 to reflect the concept of importance and significance matrixes results in the following:

$$\sum_{m=1}^{n} \frac{I_m * S_m * R_{m,e}}{(I_m)_{\max} * (S_m)_{\max} * (R_{m,e})_{\max}} * \beta_1 * \beta_2 \tag{6}$$

where, in addition to the previously defined terms, I_m is the assemblage of importance values associated with each factor, R, of m factors, and S_m is the significance function associated with each factor, R, of m factors. The subscript max indicates the maximum values possible for each factor or rating. The interpretation of the importance weight must consider the degree of correlation between that factor and the rate of decay of the corresponding bridge element. To simplify the resolution of I_m consider five categories of importance:

0: Not applicable or not important;

2: Of minor importance in establishing the rate of underwater deterioration;

4: Average importance. The factor is known to be a general indicator of the rate of underwater deterioration;

6: High importance. The factor has been proven to be a strong representative of the rate of conditional regression; and

8: Extremely important. The factor is entirely representative of the current underwater condition or the rate of change in the underwater condition of the element, or both.

In a similar manner, S_m may be objectively or subjectively determined. In establishing a decision hierarchy for significance, two elements must be considered: Does the magnitude of the factor indicate that the structure is experiencing conditions that are conducive to accelerated decay? and Does the magnitude of the factor reflect a reasonable probability that the structure will enter a condition requiring repair or maintenance before the next normal inspection cycle (5 years)? Applying the levels of significance to a five-point scale results in the following delineation of S_m:

1: The magnitude of this factor (relative to the range of values expected for that factor) indicates that the factor is insignificant in establishing a critical rate of decay or the probability that the structure will enter a state of disrepair within the following 5-year period, or both;

3: The magnitude of this factor (relative to the range in values expected for that factor) indicates that the factor holds average significance in establishing a critical rate of underwater decay or the probability that the structure will enter a state of disrepair within the following 5-year period, or both; and

5: The magnitude of this factor (relative to the range in values expected for that factor) indicates that the factor is highly significant in establishing a critical rate of decay or the probability that the structure will enter a state of disrepair within the following 5-year period, or both.

For both I_m and S_m, the scale is continuous, with the intermediate (even) values used to describe value significance levels that fall between those specifically outlined.

The importance, significance, and β-factors generated in the remainder of this paper are based on the subjective as well as objective statistical interpretation of the inspection results from the latest survey of underwater structures in Louisiana. The discussion that follows is best viewed as a structured methodology for developing a priority equation incorporating user-defined input and requisite output data.

The importance of age (hereafter denoted as the factor AGE) as a determinant of underwater condition is logically of high importance, given the time-dependent nature of deterioration in any form. Previous regression investigations have graphically illustrated the relationship between condition and AGE for underwater substructures; therefore, the importance factor for AGE will receive an importance weight of 8 for all material types:

$$I_{\mathrm{AGE}} = 8.0 \tag{7}$$

As the structure ages, of course, the significance of AGE in determining the probability that repair is (or soon will be) required increases by some degree. This understanding is supported by the values indicated in Table 4, which describe the percentage of bents awarded an FOVR less than 5—the point at which maintenance action is suggested or required. With the percentage of bents increasing by a factor of 10 or more from the earliest to the latest age groups (depending on material type), the following chart is presented as a proposed breakdown of S_{AGE} by age group:

- Concrete bents

$$S_{\mathrm{AGE}} = 1.00 \quad (\mathrm{Age} < 20) \tag{8}$$

$$S_{\mathrm{AGE}} = 2.00 \quad (20 \le \mathrm{Age} \le 40) \tag{9}$$

$$S_{\mathrm{AGE}} = 5.00 \quad (\mathrm{Age} > 40) \tag{10}$$

- Steel bents

$$S_{\mathrm{AGE}} = 1.00 \quad (\mathrm{Age} < 20) \tag{11}$$

$$S_{\mathrm{AGE}} = 4.00 \quad (20 \le \mathrm{Age} \le 40) \tag{12}$$

$$S_{\mathrm{AGE}} = 5.00 \quad (\mathrm{Age} > 40) \tag{13}$$

- Timber bents

$$S_{\mathrm{AGE}} = 3.00 \quad (\mathrm{Age} < 20) \tag{14}$$

$$S_{\mathrm{AGE}} = 3.00 \quad (20 \le \mathrm{Age} \le 40) \tag{15}$$

$$S_{\mathrm{AGE}} = 5.00 \quad (\mathrm{Age} > 40) \tag{16}$$

Although the factor AGE could serve as an indicator of the probability that a structure is in need of short-term maintenance, the ADR should serve as a measure of how the in situ environment will dictate the probability that the structure will soon enter such a condition.

Similar to AGE, the factor explicitly describes the rate of change of the overall underwater condition rating; thus ADR will receive the highest importance weight for all material-type designations:

$$I_{\mathrm{ADR}} = 8.0 \tag{17}$$

The degree of significance allotted to the ADR will be indexed to the magnitude of the term with the understanding that the value describes the likelihood that the condition will change before the following inspection cycle. For the given 5-year standard cycle, a structure would need to demonstrate an average annual deterioration rate of 0.200 points per year to drop one point in overall rating before the next inspection cycle. For the results of the latest underwater survey in Louisiana, 5.6 percent of the bents exceeded this in the factored ADR. A further breakdown shows that 9.0percent of the bents exceeded 0.150 points per year in ADR, 17.6 percent exceeded 0.100, and 43percent exceeded 0.050. The median ADR for Louisiana bents was 0.042 points per year.

The significance factor must assign a proportionately higher weight to the appraisals of those bents that are experiencing characteristically high deterioration rates, particularly those in excess of 0.200 points per year. Obviously, to achieve this goal, the significance value must be indexed to a category of ADR:

$$S_{ADR} = 1.00 \text{ for ADR} < 0.010 \tag{18}$$

$$S_{ADR} = 2.00 \text{ for } 0.010 \le \text{ADR} \le 0.030 \tag{19}$$

$$S_{ADR} = 3.00 \text{ for } 0.030 < \text{ADR} \le 0.075 \tag{20}$$

$$S_{ADR} = 4.00 \text{ for } 0.075 < \text{ADR} \le 0.200 \tag{21}$$

$$S_{ADR} = 5.00 \text{ for ADR} > 0.200 \tag{22}$$

When establishing an inspection priority based on overall underwater condition ratings, an effort should be made to ensure that single critical subcomponent ratings are not lost in the production of the general priority. The subcomponent ratings are considered in establishing the overall rating, as discussed earlier, but the ADR of the structure will not wholly depict the deterioration rate in any particular subcomponent rating. The inspection priority must ensure that a "weak link" in the structural system does not develop over the normal inspection cycle. To account for this potential oversight, the deterioration rate in the subcomponent, or SDR, shall be considered a factor in establishing an inspection priority for the structure.

The SDR is a strong indicator of the rate of deterioration but is not wholly indicative of the condition of the overall structure and thus will receive an importance value of:

TABLE 4 Percentage of Bents Requiring Maintenance

Age Group	All Materials	Concrete	Steel	Timber
All Ages	9.67	5.92	5.63	12.1
[0 to 20]	5.95	2.67	0.00	10.7
[20 to 40]	7.22	3.45	16.7	10.3
[40+]	20.6	21.7	*	19.7

* Insufficient data.

$$I_{\mathrm{SDR}} = 5.00 \tag{23}$$

Following the same rationale as with the ADR factor, the significance of SDR will follow the breakdown:

$$S_{\mathrm{SDR}} = 1.00 \text{ for SDR} < 0.010 \tag{24}$$

$$S_{\mathrm{SDR}} = 2.00 \text{ for } 0.010 \leq \text{SDR} \leq 0.030 \tag{25}$$

$$S_{\mathrm{SDR}} = 3.00 \text{ for } 0.030 < \text{SDR} \leq 0.075 \tag{26}$$

$$S_{\mathrm{SDR}} = 4.00 \text{ for } 0.075 < \text{SDR} \leq 0.200 \tag{27}$$

$$S_{\mathrm{SDR}} = 5.00 \text{ for SDR} > 0.200 \tag{28}$$

The high concentration of bridges experiencing much-higher-than-average deterioration within the coastal regions will be considered in the general β_1 factor. Coastal structures will be defined as elements which, according to LDOTD data base latitude and longitude descriptions, fall at a latitude of less than 30 degrees north latitude for longitudes between 91 degrees 30 min west and 94 degrees west, or at a latitude of less than 29 degrees 30 min north for longitudes between 89 degrees west and 91 degrees 29 min 59 sec west.

The relative increase in the deterioration of structures along the coast is substantial (ten times larger in some cases) compared with similar structures located inland, which should, on average, require a decrease in inspection cycle and greater inspection priority. Consequently, the β-factor for coastal structures will increase the priority by 25 percent for all applicable factors such that

$$\beta_1 = 1.25 \text{ for coastal structures} \tag{29}$$

Similarly, the β_2-factor will incorporate the correlation between the substructural rating assigned by the inspector performing the biennial above-surface bridge evaluations (SSR) and the factored overall underwater condition rating (FOVR) derived from the diver evaluation of the same timber bent. The ratio of SSR and FOVR may thus be utilized to determine the β_2-factor, such that

$$\beta_2 = \frac{FOVR}{SSR} \text{ for age-grouped timber} \tag{30}$$

The β_2-factor should be applied only if it increases the priority rating (i.e., is greater than 1.0) and, since the correlation between SSR and OVR was marginally significant (recall $0.746 > \rho > 0.877$), the factor should be limited to a reasonable value of 1.2:

$$1.0 \leq \beta_2 \leq 1.2 \tag{31}$$

The contribution of a single structure to the integrity of a bridge system is established by transportation officials on consideration of the bridge's traffic volume, physical dimensions and alignment, load rating, detour length, district priority, functional classification, age, and prior appraisal ratings. Utilizing a weighted point system, LDOTD engineers determine the bridge replacement priority and record the four-digit numerical evaluation on the Structure Inventory and Appraisal (SIA) sheet maintained for each bridge in the state system.

Because all bridge structures undergo the same replacement priority policy, there is no need to normalize the DOTD rating; thus the value itself will define the β_3-factor representing bridge criticality to the bridge network. To allow for the comparison of relative priorities independent of the bridge replacement priority, however, the routine will output priority rankings inclusive and exclusive of replacement priority (P_e and P_e', respectively). Retrieving the state priority point rating from the SIA sheet, the β_3-factor may be simply established as

$$\beta_3 = \text{state priority rating} \tag{32}$$

BRIDGE INSPECTION PRIORITIES: DECISION FLOW PROCESS

A sequence of operations used to develop importance, significance, and β-factors and the resulting bent inspection priorities for Louisiana bridges is outlined in Figure 1. The decision flow followed a basic four-step prioritization process:

1. Retrieval of electronically stored bridge inspection data/descriptive information;
2. Division of the data set by age/material/structure-type subsets;
3. Internal computation of bridge regression behavior and the logical assignment of pertinent weighting factors; and
4. Generation of a singular underwater bridge inspection priority value with and without the replacement priority considerations (referred to as the "priority rating" and "priority factor," respectively).

During the computational process, the system searched for and flagged unusually low rating values in addition to calculating priority rankings. The actual value of P_e is of little significance in itself but it does provide a standardized measurement for comparing the deterioration of a mixed population of bridge bents. In combination with the listing of critical subcomponent ratings, the priority value will allow bridge maintenance planners to plan both the level and interval of future underwater inspections.

CONCLUSIONS

The use of computers to store bridge inspection results has allowed meaningful statistical comparisons of the data thanks to the ease of data retrieval and mathematical manipulations. In the preceding discussion of deterioration in underwater bridge bents in Louisiana, computerized analysis has shown the rate of underwater decay to vary during the structure's lifespan and to be related to one or more of a set of bridge descriptive parameters.

Timber bents have demonstrated a strong correlation between the substructural condition assessed during biennial above-surface surveys and the underwater condition rating assigned by the diver. The strong correlation between these ratings can allow bridge engineers to use the frequent above-water surveys as a tool for determining the possible existence of subsurface deterioration in bridges using timber bents.

In Louisiana, bridge location must be considered when determining a bent's propensity for underwater deterioration. Environmental conditions found along the coastal regions of the state were shown to adversely affect the rate of change in underwater condition rating.

Taking all these observations into account, a decision flow process has been presented that permits the numerical assessment of underwater bridge inspection priorities given the results of the underwater inspections along with certain bridge descriptive param-

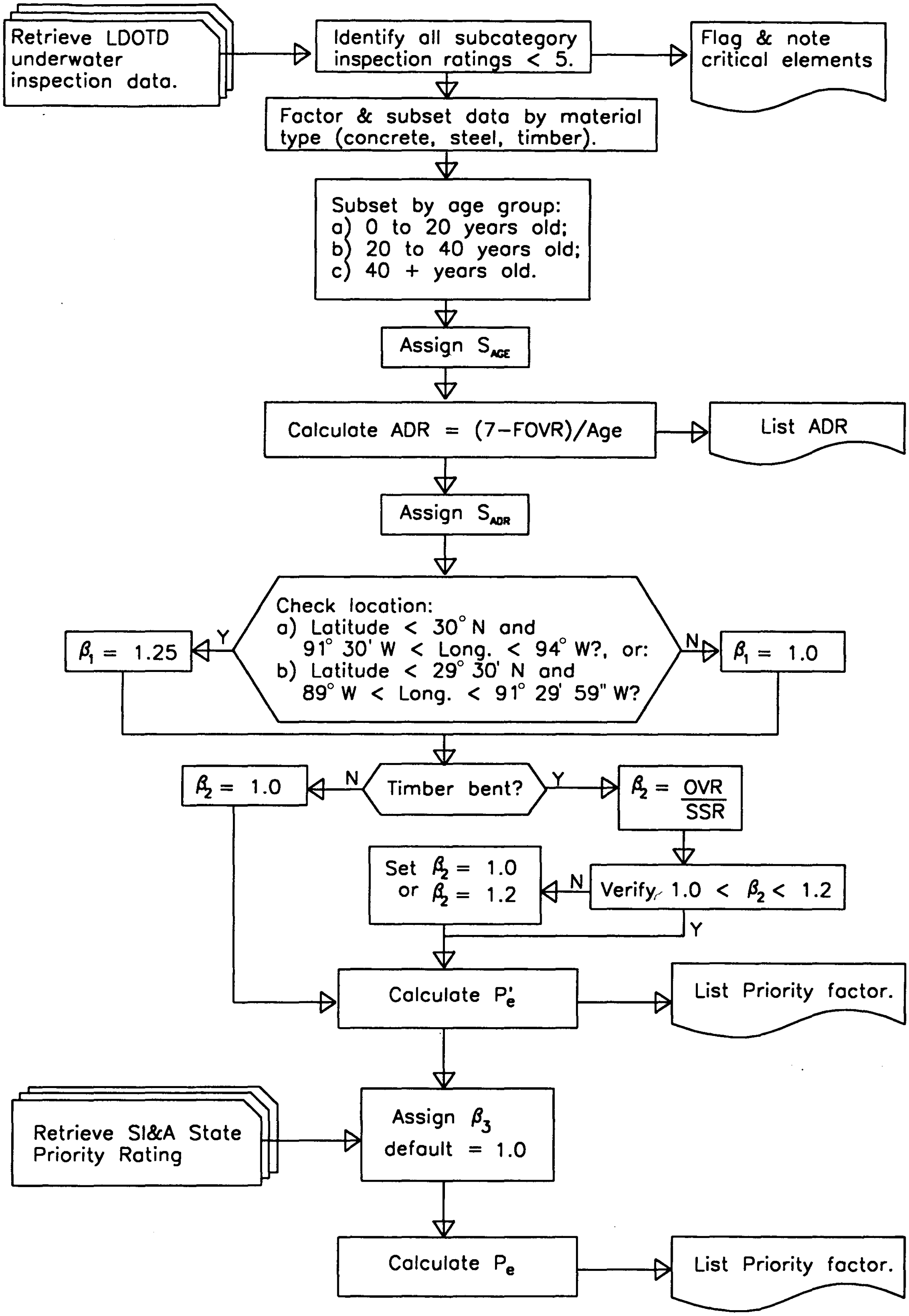

FIGURE 1 Decision flow process for establishing underwater bridge inspection priorities.

eters. The use of such a process, in conjunction with the current experienced-based method of determining inspection priorities, will allow the limited funding for future inspections to be allocated in the most effective manner.

Still, further investigations using the results of future underwater inspection programs on the same bridge population are warranted to support the relationships presented in this paper. The methodology followed in determining the structural decay characteristics for bents should also be applied to both piers and abutments to ascertain the variations in behavior based on structure type. Moreover, future investigations using the results of underwater inspections need not be limited to the area of structural decay. The same research methodology can be applied to develop a scour propensity rating based on known parameters that can be proven to affect the structures' scour condition rating.

This study provides a framework for a subset of a bridge management system related to underwater bridge components. Using the Louisiana inspection ratings and focusing on material degradation of bents only, all bridges in this subset were prioritized. With only minor changes in the type of data considered, the same methodology can be used to include all bent and pier types, as well as the effects of stream bed scour.

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