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Estimating Risk from Spillway Gate Systems on Dams Using Condition Assessment Data

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Construction Engineering Research Laboratory

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Estimating Risk from Spillway Gate Systems on Dams Using Condition Assessment Data

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ABSTRACT: Inland waterways maintained by the U.S. Army Corps of Engineers carry about 17% of the nation's intercity cargo, so service interruptions related to waterway infrastructure failure can cause substantial economic loss. Maintenance and repair (M&R) requirements for navigation structures compete for funding with every other national priority, however, and Federal budgeting decisions are determined largely on the basis of net benefit to the nation per dollar invested. The Corps uses analytical tools and methods to help objectively determine project benefits versus costs. In Corps cost/benefit analyses for navigation structures, reducing the risk of failure through repair or rehabilitation is quantified as a benefit. Conventional reliability-based risk analysis is costly and complex, however.

This study investigated the adaptation of an existing condition indexing (CI) methodology to assess overall structural risk and failure probability. It was concluded that a risk-based analysis, using the well established concepts of a reliability index, failure probability, hazard function, and cost/benefit analysis, is possible and feasible. Because CI data have not been systematically collected and are not available, the methodology proposed here remains untested. A number of reasonable assumptions made in this study have not yet been verified using actual CI data collected over time from existing projects.

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Conversion Factors

Units of measure used in this report can be converted to SI* units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	0.00001638706	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(5/9) x (°F – 32)	degrees Celsius
degrees Fahrenheit	(5/9) x (°F – 32) + 273.15.	kelvins
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
horsepower (550 ft-lb force per second)	745.6999	watts
inches	0.0254	meters
kips per square foot	47.88026	kilopascals
kips per square inch	6.894757	megapascals
miles (U.S. statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
square miles	2,589,998	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

* *Système International d'Unités* (International System of Measurement), i.e., the metric system.

Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Risk Analysis for Dam Safety (RADS) Research and Development Program. The study was conducted under RADS Work Unit 33262, "Probability of Failure of Gates, Equipment, and Warning Systems." Robert C. Patev, formerly of U.S. Army Engineer Research and Development Center (ERDC), and Stuart D. Foltz, Construction Engineering Research Laboratory (ERDC-CERL), were the co-project managers for this research. Joseph A. Padula, Information Technology Laboratory (ERDC-ITL) is the current project manager.

Dr. Tony C. Liu was the RADS Coordinator at the Directorate of Research and Development, HQUSACE. Dr. Mary Ellen Hynes of the U.S. Army Engineer Research and Development Center (ERDC) was the Laboratory Manager for the RADS Program. H. Wayne Jones, ERDC-ITL, was the RADS Program Manager. The work was performed under the general supervision of Dr. Jeffery P. Holland, Director, ERDC-ITL; and Dr. Alan W. Moore, ERDC-CERL.

The authors wish to express appreciation to Rick Norton of the Naval War College (NWC) who served as Faculty Advisor; and to Carnes Lord, Jim Giblin, Chuck Hodell, and Geoffrey Wawro, who served on the NWC Advanced Research Council.

At the time of publication of this report, Dr. James R. Houston was Director of the ERDC and COL James R. Weller was Commander and Executive Director.

1 Introduction

1.1 Background

The U.S. Army Corps of Engineers (USACE) is responsible for maintaining and operating the nation's navigable waterways and is the primary agency for maintaining Federal flood control dams. This mission requires a vast amount of infrastructure, including 270 navigation dams, 350 reservoir dams, and 238 lock chambers (Bullock and Foltz 1995). The inland waterways maintained by the Corps of Engineers are used to transport 630 million tons of consumer goods every year with an annual value of $73 billion. Those waterways carry about 17% of the nation's intercity cargo, representing a significant portion of the U.S. economy (HQUSACE 2004). Therefore, interruptions of service related to waterway infrastructure failure are a potential source of substantial economic loss.

The U.S. inventory of navigation structures deteriorates over time and requires billions of dollars for maintenance, repair, and upgrade. More than half the locks and dams operated by the Corps are over 50 years old. In 2002, a critical maintenance backlog of $587 million for navigation was reported (Flowers 2002). The Fiscal Year (FY) 2003 Civil Works budget was $4.3 billion, of which $1.98 billion (about 46%) was allocated for General Operation and Maintenance including maintenance and other costs related to infrastructure condition and performance. The Construction – General portion of the budget was $1.44 billion, including major rehabilitation and repair. Within the Corps budget, navigation and flood control structures compete with water control, hydropower, ecosystem restoration, and recreation facility projects. After the terrorist attacks of September 11, infrastructure security became a much higher priority, representing additional competition for funds within both the Corps and the overall Federal budget. Furthermore, these requirements compete with every other national priority in the Congressional appropriations process. Consequently, construction, maintenance, and operations dollars are expected to remain scarce, so effective allocation of those resources is an ongoing concern.

The Corps uses "Principles for Improving Program Performance" (OMB 2004, p 257) to allocate budget resources, which encompass a reliance on objective criteria, cost/benefit analyses, and rank-order comparison of competing requirements. The goal of these principles is to fund activities that yield the greatest net benefit to society per dollar invested (OMB 2004). Because the decisions must be supported quantitatively, the Corps uses analytical tools and methods to help determine the value of a project's benefits relative to its costs. In other words, the Corps must invest in the maintenance of infrastructure based on the benefits that will accrue.

In most cases, maintenance dollars should be allocated to projects where doing nothing poses the greatest risk (as defined above). In typical cost/benefit analyses, the risk reduction achieved by repairing or rehabilitating a structure is considered to be a benefit. A major Civil Works rehabilitation project typically costs more than $8 million and requires a time-dependent reliability analysis as justification (EP 1130-2-500). Whether assessing risk or quantifying the benefits of avoiding risk, a dependable analysis method is needed to quantify the probability of infrastructure failure under existing and future conditions.

Reliability analysis involves defining all random variables, predicting how loads will change and the structure will deteriorate over time, and quantifying the probability of failure of the structure at discrete points in time. The probability of failure is defined as the probability that demand on the structure will exceed its capacity. These point-in-time probabilities of failure are converted to a hazard function that describes the probability of failure in a particular year assuming that the structure will not have failed by that time. Then, to define the risk to the structure, the hazard function is applied to an event tree that incorporates both the likelihood and consequences of failure. The defined risk is used in the cost/benefit analysis to assess the effectiveness of the proposed major rehabilitation. A similar procedure is applied to perform a reliability analysis on electrical and mechanical equipment used in Civil Works projects except that the reliability is based on previous statistical performance rather than a capacity/demand analysis.

1.2 Objective

The objective of this work was to investigate whether the existing Condition Indexing (CI) methodology for spillway gate systems on dams (Chouinard et al. 2003) can be used as a basis for assessing structural risk and probability of failure.

1.3 Approach

A survey of current reliability analysis and CI methods was conducted. Opportunities and issues associated with using CI data to quantify risk were examined. Dam spillway gate system operations were reviewed to determine the requirements for a reliability analysis. A general methodology was then developed for using CI ratings to quantify risk, and the procedure was demonstrated using both a simple hypothetical example and a real-world dam spillway gate system (the Great Falls Spillway, a Winnipeg River hydroelectric plant managed by Manitoba Hydro). A vulnerability assessment component relating to potential terrorism was also developed and illustrated using the same hypothetical structure employed in demonstrating the general methodology.

1.4 Scope

This research focuses on the issue of failure probability, not the financial costs of infrastructure failure. The consequences of failure may be projected or quantified by other established means.

The Corps of Engineers has developed a Condition Index (CI) inspection system for various components of structures it operates and maintains. A CI is a standardized snapshot assessment of the condition of a structure based on a visual inspection. The Condition Index ranges from 0 (failed) to 100 (excellent) and was developed to assist in the prioritization of nonrecurring maintenance work. CI systems have been developed for miter gates, tainter gates, embankment dams, sector gates, hydropower equipment, and coastal projects such as breakwaters and jetties. While the CI is a valuable tool for comparing the relative condition of various structures, it does not offer a probabilistic measure of risk to a structure.

The most recently developed CI is for spillway gates on dams (Chouinard et al. 2003). This CI procedure defines the spillway gate system of a dam as a hierarchical structure consisting of systems, subsystems, and inspectable components. The various components and subsystems are assigned importance factors for each of the specific failure modes such as overtopping, failure of a gate to close, unintentional gate opening, or reservoir drawdown. The importance factors and overall condition based on component inspection results allow a condition index to be computed at every stage of the structural hierarchy.

1.5 Mode of Technology Transfer

The findings of this study demonstrate how condition indexes may be integrated into a probabilistic approach for estimating the reliability of Civil Works infrastructure components and systems. As part of a reliability approach, condition indexes may be incorporated into current USACE Civil Works policy mandating that reliability be one of two authorized justifications for rehabilitating navigation structures. The Corps has been developing similar probability-based policy guidance for dam safety risk analysis.

Because CI data have not been systematically collected and are not available, the methodology proposed in this study remains untested. A number of reasonable assumptions were made in this study, but they have not yet been verified using actual CI data collected over time from existing structures. For that reason, the analysis methods presented in the report are not endorsed by CECW-ET at this time.

2 Overview of Reliability Analysis and Condition Indexing

2.1 Risk Assessment and Reliability Analysis

Risk is defined as the combination of the probability and consequences of failure. Failure occurs when a structure no longer performs as intended. If the cost of a structural failure is $10,000 and the estimated probability of failure is 30%, then the value of the risk is considered to be $3,000. This study focuses on determining the probability of failure, not the costs.

Reliability-based methods have gained increasing acceptance in academic circles and are being adopted by engineer practitioners. Reliability methods take a probabilistic approach to designing and analyzing a structure, and the result is a reliability index or a probability of failure rather than a traditional, deterministic factor of safety. In structural design, critical factors such as loads, resistances, deterioration models, and human errors are highly random and the associated uncertainties must be quantified to adequately assess structural risk and public safety.

Reliability methods are computationally more difficult and complex than traditional deterministic methods. Such methods have only become practical as a result of great advances in computer methods and technology over the past 20 years. In their complete form, reliability methods often involve complex convolution integrals that have no closed-form solution. Simplified methods that make first- and second-order approximations have been highly successful at reducing the complexity of reliability computation while producing accurate results. Although reliability analysis often requires a large number of simulations to obtain good solutions, Monte Carlo statistical methods have produced excellent results.

2.2 Reliability Analysis of Structures

A reliability analysis begins with a limit state equation or series of limit state equations that govern the behavior of the structure. The limit state equation is typically the same design equation that is used in a deterministic approach except the parameters of every random variable have been quantified. The yield stress for steel in a deterministic design, for example, is typically 36 ksi. In the reliability-based analysis, the yield stress for steel is more appropriately defined as a normally, or log-normally, distributed random variable with a mean of 40.3 ksi and a standard deviation of 3.9 ksi (Nowak 1995). A structure is considered safe or reliable if its capacity, C, exceeds the demand, D, placed on it:

$$C \geq D \text{ or } \quad C - D \geq 0 \quad \text{or} \quad \frac{C}{D} \geq 1 \qquad (2.1)$$

The limit state surface is defined as $g(\mathbf{X})=C-D=0$ where $\mathbf{X}$ is the vector of design variables in the problem. The reliability of a structure, p_s, is the probability that the structure survives or performs safely. If the capacity, C, and the demand, D, are random and the uncertainty can be quantified, then the reliability or probability of safe performance, p_s, can be expressed as:

$$p_s = P(g(\mathbf{X}) \geq 0) = P(C - D \geq 0) = \iint_{C>D} f_{C,D}(c,d)dcdd \qquad (2.2)$$

where $f_C(c)$ and $f_D(d)$ are the probability density functions of C and D , respectively, and $f_{C,D}(c,d)$ is their joint probability density function. Similarly, the probability of failure, p_f, can be defined as

$$p_f = 1 - p_s \qquad (2.3)$$

The computation of p_s can be quite complex depending on the number and type of uncertainties, the correlation, and the number of variables that comprise C and D.

2.2.1 The Reliability Index

The most common means of communicating reliability is through a reliability index, β , which is defined as the shortest distance from the origin to the limit state surface g(**X**)=0 in standard normal space. In the case where C and D are independent and normally distributed variables, the reliability index is

$$\beta = \frac{\mu_C - \mu_D}{\sqrt{\sigma_C^2 + \sigma_D^2}} \qquad (2.4)$$

where μ is the mean value and σ is the standard deviation of the variables C and D. In this case, the reliability index can be equated to the probability of failure, p_f, as follows:

$$p_f = \Phi(-\beta) \qquad (2.5)$$

where Φ is the distribution function of the standard normal variate. For these circumstances, Table 2.1 shows the relationship between reliability index and probability of failure. When the variables are not normally or log-normally distributed, or the limit state function is not linear, the reliability index cannot be directly related to the probability of failure, but it remains a highly useful means of communicating the approximate level of reliability of a design.

2.2.2 Time-Dependency

When attempting to make decisions about a structure over its useful life, time is an important variable. Loads tend to increase over time and resistance tends to decrease as the structure deteriorates, so overall reliability can generally be expected to decrease over time. If the load and resistance of the structure can be projected for the future, the approach for time-dependent reliability is to compute the probability that a structure will perform satisfactorily for a specified period of time. Whereas probability of failure p_f is defined as the probability that an element will fail at one particular time, the cumulative distribution function $F_T(t)$ defines the probability that an element will fail at any time t :

$$F_T(t) = P(T \le t) = p_f(t) \qquad (2.6)$$

where the random variable T represents time and $t \geq 0$. The probability that a failure, $p_f(t)$, takes place over a time interval Δt is expressed as

$$f\ (t)\Delta t = P\{t_1 < t \le t_1 + \Delta t\} \qquad (2.7)$$

where the probability density function $f(t) = \frac{dF_T}{dt}$. It is assumed that the derivative exists.

Reliability is often expressed in terms of a hazard function, *H(t)* , also called the *conditional failure rate*. The hazard function expresses the likelihood of failure in the time interval t_1 to t_1+dt given that the failure has not already occurred prior to t_1 and can be expressed as

$$H(t) = \frac{f(t)}{p_s(t)} \qquad (2.8)$$

All hazard functions must satisfy the non-negativity requirement. Their units are typically given in failures per unit time. Large and small values of $H(t)$ indicate great and small risks, respectively (Leemis 1995). The hazard function is used in the cost/benefit analysis to justify a particular project.

2.2.3 Reliability of Systems

A structural system may have multiple components and failure modes. There are many advantages gained by quantifying the interrelationship between the components and analyzing a structure as a system. For example, a system analysis can reveal that some repairs are more important than others. A system analysis may also indicate that the structure as a whole may be unsafe even though each individual component may have adequate safety.

2.2.3.1 Series Systems

If the failure of any single component will lead to the failure of the entire structure, the system is considered a *series* or *weakest link* system. If a structural system is treated as a series system of *z* elements, the probability of system failure, $p_{f,series}$,can be written as the probability of a union of events

$$p_{f,series} = P\left(\bigcup_{a=1}^{z}\{g_a(\boldsymbol{X}) \le 0\}\right) \qquad (2.9)$$

where the limit state of element a is defined as $g_a(\boldsymbol{X})=0$ and $g_a(\boldsymbol{X})<0$ is the failure state. The correlation between failure modes must be taken into account. Consider a series system consisting of two components where the probability of failure of each individual component is $p_f=0.01$. If the two failure modes are independent so that there is no correlation, the failure probability of the system is

$$p_{f\ series} = 1-\prod_{a=1}^{z}(1-p_{f_a}) = 1-(1-0.01)(1-0.01) = 0.0199 \qquad (2.10)$$

If the two events are perfectly correlated, the failure probability of the system is $p_{f,series}= p_{f,a\text{-}max}=0.01$

2.2.3.2 Parallel Systems

A system is considered a *parallel* system if system failure occurs only after the failure of all components. For a parallel system, the probability of system failure, $p_{f,parallel}$ can be written as the probability of an intersection of events

$$p_{f,parallel} = P\left(\bigcap_{a=1}^{z}\{g_a(\boldsymbol{X}) \le 0\}\right) \qquad (2.11)$$

For a parallel system consisting of two components whose individual probabilities of failure are $p_f=0.01$, the system failure probability is upper-bounded (first-order) by $p_{f,\ parallel} = p_{f\ a\text{-}min} = 0.01$ if the two failure modes are perfectly correlated and lower-bounded (first-order) by

$$p_{f,parallel} = \prod_{a=1}^{z} p_{f_a} = (0.01)(0.01) = 0.0001 \qquad (2.12)$$

if the two failure modes are independent. As indicated in this simplified example, there can be huge errors if correlation is neglected (Cornell 1967).

2.3 Electrical and Mechanical Reliability

Reliability analysis for electrical and mechanical equipment is more straightforward because most electrical and mechanical components are produced or tested in sufficient numbers such that a statistical database exists based on the actual past performance of the same components (TL 1110-2-550, TL 1110-2-560)[1]. In contrast, each Civil Works structure as a system is unique and therefore has no statistically significant performance sample to draw upon. For electrical and mechanical equipment, component life is divided into an initial period where failures are high due to poor workmanship or quality control, a useful life period, and a wear-out phase during which failures are high due to aging and deterioration. The reliability or probability of survival at any point in time during the useful life period is computed as:

$$p_s(t) = e^{-\lambda t} \qquad (2.13)$$

where t is the time period and λ is the statistical failure rate, usually found in manufacturer's data or a table of equipment. TL 1110-2-560, for example, lists the failure rate of a butterfly valve as $\lambda=0.29$ failures per 10^6 operating hours and $\lambda=14.4$ failures per 10^6 operating hours for a direct current (DC) motor. Those failure rates a based on a weighted average of numerous studies compiled by the Reliability Analysis Center, Rome, NY. An adjusted failure rate λ' can be developed based on actual conditions where

$$\lambda' = K_1 K_2 K_3 \lambda \qquad (2.14)$$

The K factors are taken from tables based on general environmental conditions, stress rating, and temperature. While such factors can be helpful, they are not based on inspection or actual performance of the component being evaluated. Given the reliability at points in time, the hazard function is calculated as described earlier. The reliability of an electrical or mechanical system is computed by creating a series-parallel system of the individual components. The electrical and mechanical analysis is generally not combined with the structural reliability analysis to obtain an overall system reliability index.

2.4 Life-Cycle Analysis

Reliability methods are often used to optimize the life-cycle cost of a structure and to guide future maintenance and repair decisions. The Corps of Engineers is

[1] TL: Engineer Technical Letter.

currently using this methodology as part of the analysis and justification for major rehabilitation of navigation structures. Padula et al. (1994) explain the process in detail for the reliability of miter gates on locks to include load forecasting, deterioration modeling for corrosion and fatigue, and computation of a hazard function. Currently, reliability is computed using a Monte Carlo simulation instead of the point estimate method used in Padula et al. (1994).

Reliability methods are appropriate for maintenance and repair planning throughout the useful life of a structure. The life-cycle cost includes the costs of initial construction, preventive maintenance, repair, inspection, and expected cost of failure, among other expenses. Life-cycle optimization must balance lifetime cost against acceptable risk. Reliability methods are best for quantifying that acceptable risk. Such calculations are often made during the design phase before a structure is constructed. Reliability-based condition assessment involves quantifying the uncertainty associated with a structure's condition rating. Defining the structure's condition in probabilistic terms allows the risk analysis to be updated and the life-cycle strategy to be revised.

2.5 Limitations of Reliability-Based Methods

The biggest drawback to reliability methods is the amount of input data needed to perform a valid analysis. The most rigorous option is to conduct tests to obtain all of the input data needed for a specific project. Such tests might include strength tests of concrete, traffic surveys on a bridge, corrosion rate tests of steel, storm data analysis at the project site, etc. This approach is usually prohibitively expensive both in terms of money and time. Past experience and previous studies in the literature are a less costly source of data, but the results may not be applicable to the project of interest. Sensitivity analyses on the respective variables will often help to identify which variables merit the most scrutiny. Unfortunately, reliability results are only as valid as the input data that support them. Ultimately, when sufficient data are lacking, a degree of subjectivity is required in the form of making assumptions, soliciting expert opinion, extrapolating existing data, choosing which situation best applies, and inferring human capabilities. Some risk analyses performed by the Corps have resulted in subjective probability estimates that differed by more than two orders of magnitude between participants. That range of results for any given case obviously lacks the precision needed for effective decision-making.

In practice, the reliability analysis is often based on one critical failure mode due to the complexity of considering multiple variables. On a miter gate, for example, reliability analysis addresses stress on the main girder or the number of fatigue cycles. In reality, there are many other distresses that could prevent a miter gate from performing as intended, such as the condition of the diagonals, the anchorage arm, the motor and gear assembly, the alignment of the gate, etc. No effective approach to incorporate all important variables into reliability analysis for a structural system has yet been developed. Russell and O'Grady (1996) introduce a risk-based life-cycle lock repair model that incorporates a systems approach to analyzing a lock structure, but the probabilistic condition assessment is crude.

2.6 Condition Index Assessment

2.6.1 Origins of Condition Indexing

To date, the most effective method for accounting for every critical aspect of structural behavior has been the Condition Index, or CI. A CI is a numerical rating, ranging from 0 – 100, that describes the condition of a structure at a specific point in time (Foltz, Howdyshell, and McKay 2001). The CI is based on a series of observations by an inspector that is related to a set of objective condition criteria. At the component level, the inspector classifies what he or she sees into a predefined descriptive category that best matches the observation. Some CIs incorporate objective measurements but others do not. At the structure or system level, the CI is a composite score derived from inspector observation using *importance* or *weighting* factors. The CI methodology was developed to prioritize and justify non-recurring operations and maintenance investments in Corps infrastructure. Table 2.2 shows the CI rating scale, which generically applies to any type of structure. The condition of a structure is divided into seven categories that describe distinct levels of deterioration.

A CI system is developed specifically for the type of structure being evaluated. The first CI system, PAVER, was developed for U.S. Air Force runways (Shahin et al. 1976) and was later adapted to determining the serviceability of roads and other vehicle pavements (Shahin and Walther 1990). The Corps has developed analogous systems for dams, locks, and other navigation structures (Greimann et al. 1990). Since the Civil Works CI program began in the mid-1980s, CI systems have been developed for miter gates, tainter gates, embankment dams, sector gates, hydropower structures, and coastal projects such as breakwaters and jetties. Many of the narrative terms used to describe a distress are subjective words such as *minor*, *major*, *extensive*, *constant*, *increasing*, and *significant*. Although such descriptions are the best that can be applied to many areas, they are not easy to quantify in a repeatable numerical way. A few condition states are quantified on the basis of objective measurements, however, such as the depth of erosion categorized as 0 – 1 ft, 1 – 3 ft, or greater than 3 ft (Andersen et al. 1999).

2.6.2 Potential Reliability Applications of Condition Indexing

The benefits of the CI methodology include a standardized approach to quantifying condition, identification of specific problems in a structure, establishment of a condition history for an individual structure, establishment of a database for the deterioration of a class of structures, prioritization and efficient allocation of scarce maintenance funds, and guidance for less experienced inspectors on what to look for (Foltz et al. 2001). An important potential benefit is the incorporation of CIs into risk and reliability analysis methods. Foltz et al. (2001) discuss the use of CIs in risk analysis, as an input to reliability, and as an approximation of reliability. They concluded that because CIs do not examine either the load or the resistance of a structure, it is not possible for CI data alone to provide a direct measure of reliability. However, CIs may be used to improve the results of reliability analysis.

The CIs focus on observable deviations from a desired condition. The component observations, if they are relevant and sufficiently detailed, could be used to update or enhance a reliability analysis. Estes et al. (2004) illustrated how quantified CI data could be used to update the time-dependent reliability analysis of a miter gate. Mlaker (1994) and Ayyub et al. (1996) treated the CI ratings as the relevant random variable to compute the reliability of hydropower equipment. The study concluded that the database on hydropower equipment was too sparse to draw valid conclusions, but the technique showed promise if sufficient data were available.

Because CIs are based on structural behavior and response, they may serve as a kind of proxy for reliability. If so, using CI information in a risk-based analysis could offer a low-cost alternative to the type of complex, expensive reliability studies that can only be justified for large projects. Using CI information as a lower-cost option allows cost-effective application of reliability to smaller projects and would support better-informed rehabilitation budgeting decisions.

2.7 Illustrating the Probabilistic CI With an Automobile Analogy

The difference between the traditional reliability analysis and the condition index may best be described using an automobile as an analogy. A reliability analysis of an automobile might pick the most critical failure mode such as the performance of the engine. The capacity is the horsepower provided by the engine. The demand would be the horsepower needed to get the fully loaded automobile over the steepest hill that it is likely to encounter. The engine will degrade over time as it ages and wears. The probability of failure is the probability that the demand on the engine would exceed its capacity. When that probability becomes too high as determined by an economic analysis, the engine or the entire automobile is replaced.

In reality, nobody replaces an automobile using that logic. An automobile is a complex system consisting of a drive train, electrical system, body, fuel system, and accessories. For most, a replacement decision is based on a complex combination of variables such engine miles, tire wear, body rust, inoperable radio, old alternator, and worn brake pads. A condition index for the automobile would be derived from inspecting the car for all relevant variables such battery age, corrosion, shock absorber damping, engine compression, steering tightness, etc. Based on the relative importance of each of these observations, a general CI for the automobile system is created. As a transmission is replaced or new tires are purchased, the CI for those components would improve substantially and the CI for the automobile system would improve relative to the importance of those components and thus, the car is less likely to need replacement.

If an individual owned a fleet of automobiles, that system CI would be very helpful in deciding which cars to replace and which would benefit most from an overhaul. If the CI data were probabilistic in nature and failure was defined by the condition at which components or systems are replaced, then a risk assessment would be possible. That is the approach this study will take.

2.8 Incorporating CI Data Into Probabilistic Analysis

There is no way to use CI data to replace the traditional reliability analysis for a structure because the procedures are too dissimilar and are designed to serve two different purposes. It may however be possible to transform the condition index system, which is deterministic in nature, into a probabilistic analysis. The result would allow the same stochastic techniques involving probability of failure and hazard functions to be used in a cost/benefit analysis. This report will propose such an approach by treating the condition index as a random variable, making initial assumptions that would eventually be modified over time as a database is established, and using existing condition state definitions so that current methods and accumulated data remain valid.

Table 2.1. Relationship between reliability index and probability of failure for normally distributed variables and linear limit state functions.

Reliability Index (β)	Probability of Failure (p_f)
0.0	0.5000
1.0	0.1587
2.0	0.02275
3.0	0.00135
4.0	0.0000316
5.0	0.000000286

Table 2.2. Condition index rating scale for inspected structures (Foltz et al. **2001).**

Zone	Condition Index	Condition Description	Recommended Action
1	*85 – 100*	*Excellent:* No noticeable defects. Some aging or wear may be visible.	Immediate action is not required.
	70 – 84	*Good:* Only minor deterioration or defects are evident.	
2	*55 – 69*	*Fair:* Some deterioration or defects are evident, but function is not significantly affected.	Economic analysis of repair alternatives is recommended to determine appropriate action.
	40 – 54	*Marginal:* Moderate deterioration. Function is still adequate.	
3	*25 – 39*	*Poor:* Serious deterioration in at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, rehabilitation, or reconstruction. Safety evaluation is recommended.
	10 – 24	*Very Poor:* Extensive deterioration. Barely functional.	
	0 – 9	*Failed:* No longer functions. General failure or complete failure of a major structural component.	

3 Overview of Spillway Gate Systems on Dams

3.1 Spillway Gate Operations

The purpose of a spillway on a dam is to convey water from the reservoir to the tail water for all discharges up to design flood level (EM-1110-2-1603). The flow of water is controlled by gates that are raised and lowered to permit the passage of water. The most common gates on spillway crests and navigation locks are vertical lift (or roller gates) that are lifted directly upward and tainter gates that are radial in form and rotate about trunnion pins that are anchored to adjacent piers. Both types of gates are lifted with a hoist or a crane. Figure 3.1 (FEMA 2005) shows a vertical lift gate failing on the Folsom Dam, near Sacramento, CA. Figure 3.2 (Foltz, Howdyshell, and McKay 2001) shows the Stewart Mountain Dam, AZ, with a series of tainter gates. Both gate systems consist of the gate, a supporting structure, a lifting device in the form of a crane or a motor, cables, gears, and an electrical power supply.

Tainter gate systems tend to require less maintenance than lift gates. They do not require a tower to house mechanical equipment, are less susceptible to fatigue, and for most applications they are more economical in terms of both first cost and life-cycle cost. The radial form provides an efficient transfer of load through the trunnion, allowing for a lower hoist capacity. No gate slots are required and tainter gates have a fast operating speed (EM 1110-2-2702). The advantages of lift gate systems are a shorter length of spillway pier required, ease of fabrication, reduced construction time, and simpler design of supports due to the single-direction lifting load. Because both examples cited in Chouinard et al. (2003) are vertical lift gate systems, this study focuses on those structures.

Vertical lift gates rely on horizontally framed girders as their main support members. The girders reinforce a thin metal sheet that forms the skin plate. Intercostals provide intermediate support in the vertical direction. Vertical lift gates may also be formed as trusses or tied arches. Wheels, revolving around a fixed axis, are attached to the ends of the gate. The wheels roll in a prefabricated slot or on rails mounted in a concrete slot as the gate is raised and lowered. A tractor, slide, or stoney may be used instead of fixed wheels. The gate is lifted using an electric motor, cable drum hoist, hydraulic cylinders, or a crane (EM 1110-2-2701).

3.2 Spillway Reliability

The spillway gate is expected to withstand a variety of loads, including hydrostatic, hydrodynamic, gravity, equipment, impact, earthquake, downpull, thermal, and wind loads. These loads all have associated uncertainties as represented by the random variables that describe them. A reasonable combination of loads is considered, and those affect the structure in terms of member stresses, deformations, vibrations, fatigue, etc., i.e., the demand on the structure. The spillway gate is designed with a certain capacity to resist those forces. There are uncertainties associated with the strength of the material, the dimensions of the cross-section, and the theoretical models that are quantified as random variables.

The probability of failure is defined as the probability that demand on the structure will exceed its capacity. A reliability analysis would typically focus on the stress on the horizontal girders. Deflections and vibrations are usually considered serviceability criteria and not as critical as the strength-based stress computations. In a time-dependent reliability analysis, a model and its quantified uncertainties are needed to predict how the structure will deteriorate over time through such mechanisms as section loss due to corrosion. The probability of failure over time leads to the hazard function, as described in Chapter 2.

For the vertical lift gates, which are subjected to repeated cyclic loading, fatigue may be the critical failure mode. For fatigue, the reliability is based on critical welded connections on downstream bracing members that are connected to the downstream flange of the horizontal girders (EM 1110-2-2701). The applied stress range, number of loading cycles and the magnitude of the stress concentrations are critical considerations. The forecasting of the load cycles and their magnitudes provides the time-dependent analysis.

3.3 Spillway System CI Methodology

Chouinard et al. (2003) developed a condition assessment methodology for dam spillway gate systems using CI ratings. Gate system equipment encompasses electrical, mechanical, force transmission, and gate structure subsystems. The operational subsystems encompass information gathering, decision-making, and access functions. Dam safety considerations included the failure modes of overtopping during a design flood, overtopping during load rejection, unintentional opening of the gate, failure to close the gate, and reservoir drawdown. The spillway is described using a seven-level hierarchy, as shown in Figure 3.3. Level 7, the lowest structural level, consists of individual components (shown in light blue; light in black/white version) where an inspector provides a rating corresponding to a descriptive table. Table 3.1, for example, shows the table for the hoist brake, a component of the force transmission subsystem. A word description of the component function is provided along with a description of both excellent and failed behavior. Table 3.1 lists four condition states (or indicators) with a word description of each. Condition state 1 (CS1), for example, is described as, "Can arrest motion at any position, not seized." The inspector observes the brake hoist and relates his or her observations to the appropriate condition state. A range of CI scores is provided for each category.

Of the 70 component condition tables in the study, all are based on narrative description rather than quantitative data. Chouinard et al. (2003) offer no guidance as to whether the inspector chooses the highest, lowest, or some average score for the rating. Andersen et al. (1999), use these same types of component tables, stating that the CIs based on those component tables are subjective and appears to leave it to the individual inspector to choose an appropriate value.

The higher-level CI scores for subsystems, systems, and eventually the structure (shown in yellow in Figure 3.3; dark in black/white version) are derived from the component CI scores and the importance values from the previous level. The importance factors (I) are based on expert opinion, and the sum of the importance factors at any given level is equal to 1.0. Given the CI and I values from the lower-level elements, then the CI for the next-higher level is:

$$CI_{level_{i-1}} = \sum_{j=1}^{n} I_j CI_{j,level_i} \qquad (3.1)$$

where there are *j* elements in level *i*. Equation 3.1 is used for series and parallel arrangements of components. *Series* means that the system fails if *any* element in it fails. *Parallel* means that *all* elements must fail for the system to fail

This methodology provides a deterministic CI rating at every structural level that can ultimately be traced back to inspectable components. The analysis includes a number of relevant variables such as the ability to gather information, make decisions, and gain access, which are not traditionally included in a structural assessment. The importance factors and CI ratings are then used to compute priority rankings for maintenance of the various components. Chouinard et al. (2003) use the Paugan (Hydro-Quebec) and Great Falls (Manitoba Hydro) spillways as illustrative examples.

3.4 CI-Based Risk Assessment

While Chouinard's CI methodology for spillways incorporates every relevant aspect of performance, from river flow measurements and emergency generators to lifting devices and gear assemblies, the information could not be used to compute the probability of spillway failure in the traditional sense. There is no information that helps to compute stresses in members or loads over time. The information that indicates corrosion or a fatigue crack is confined to a single component table (C.66: Gate Structure) and the information is not sufficiently quantified to be useful. Similarly, the reliability of electrical and mechanical components is currently based on total operating hours and defined environment, and these factors are not addressed by CI results. Instead, the CI directly provides inspection information about the component being analyzed. One could argue that such information is a better indicator of performance reliability for a specific component, but that argument would simply reinforce the idea that traditional reliability analysis and CI ratings are too different in their purpose and scope to be interchangeable. Estes et al. (2001, 2004) describe the requirements for using CI data to complete a reliability analysis. In addition, a reliability analysis could not effectively incorporate as many variables as Chouinard et al. (2003) consider in the assessment of spillways because the analysis would be too complex.

One alternative would be to make the CI process probabilistic using the CI as the random variable. A risk analysis may then be possible relative to failure as defined within the CI methodology. While that approach would not be an equivalent replacement for a traditional reliability analysis and would carry its own set of limitations, it could provide some additional capabilities that are not available within the current deterministic CI methods. The proposed methodology is described and illustrated in Chapter 4 using a simple hypothetical structure, and then in Chapter 5 using real data from the Great Falls spillway.

Table 3.1. Component condition table for the hoist brake – part of the force transmission subsystem on a spillway (Chouinard et al. 2003).

Hoist Brake									
Function	To arrest motion of gate and hold gate in any position								
Excellent	Can arrest motion at any position, not seized								
Failed	Cannot arrest motion at any position, seizing of brake								
Indicator	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**	**Score**	**Comments**
Can arrest motion at any position, not seized							x		
Limited slippage without impacting operation; no slip but vibration				x	x	x			
Limited slippage that impacts operation		x	x						
Continuous slippage, seizing of brake	x								

Figure 3.1. Photo of gate spillway system failure on the Folsom Dam (FEMA 2005).

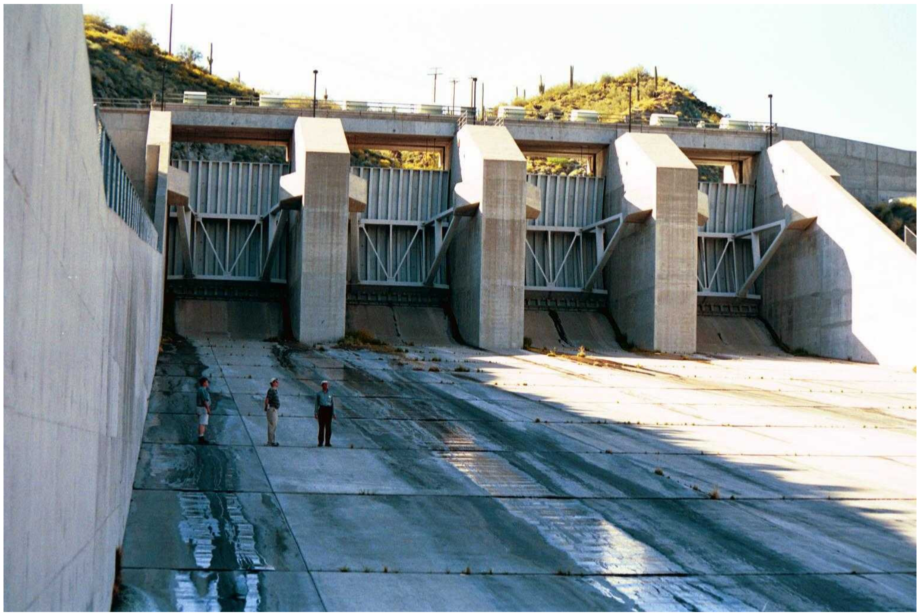


Figure 3.2. Photo of the tainter gates on the Stewart Mountain Dam.

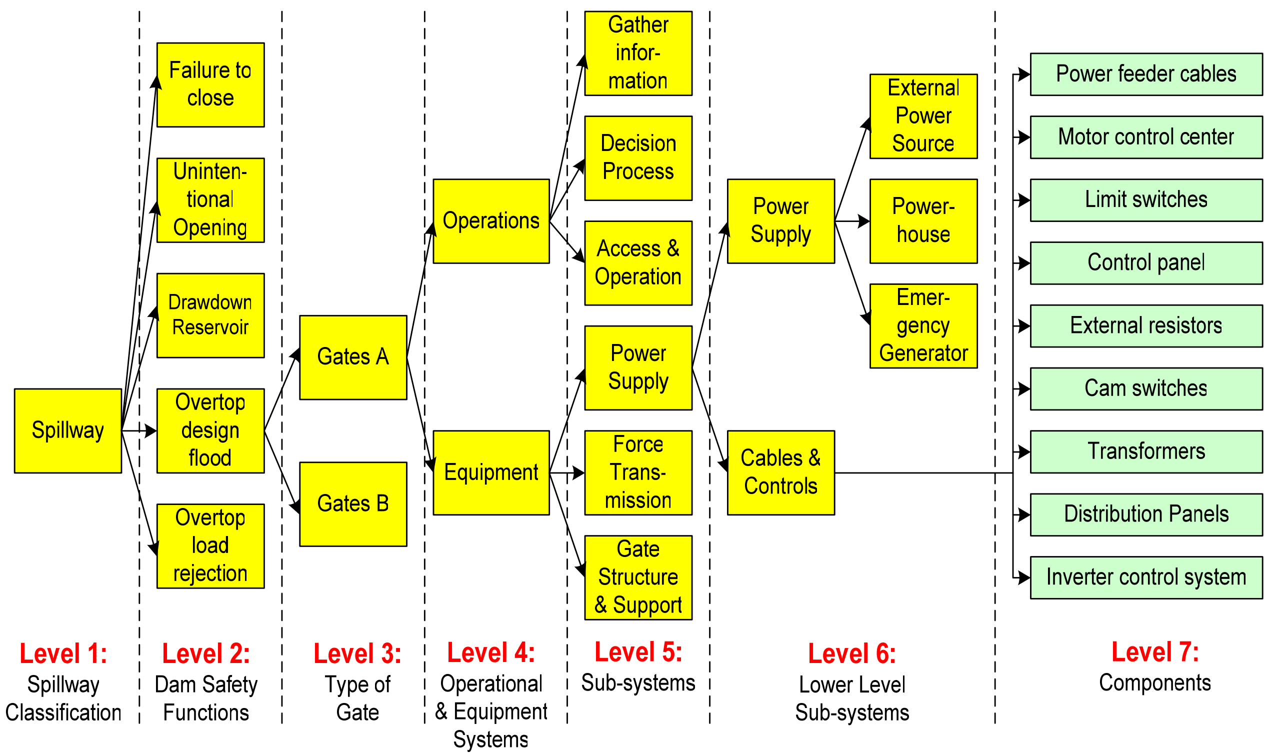


Figure 3.3. Hierarchy of spillway system for dams (Chouinard et al. 2003).

4 A Probabilistic CI Methodology

4.1 Using CI as a Random Variable

This chapter proposes a probabilistic approach to condition indexing in which the CI is the random variable. When using CI as the random variable, the probability of failure equals the probability that the actual CI rating is lower than the CI rating that defines failure:

$$p_f = P(CI_{actual} \leq CI_{failure}) \qquad (4.1)$$

4.2 Assumptions

The approach requires a number of assumptions, the validity of which may be discussed and modified as additional data are acquired. An initial assumption is that CI values are normally distributed and independent. The level of additional accuracy potentially attained using other distribution types or correlation between variables does not justify the additional complexity required.

The parameters (mean value and standard deviation) of the actual condition index CI_{actual} will be determined by the component condition table and the confidence in the inspector to correctly assign the correct condition state to an inspected component. In this study, it is assumed that the inspector will classify the structure correctly 95% of the time, although other reasonable values (90%, 80%) could be chosen. Factors such as inspector experience, quality assurance spot checks, training programs, formal certification, periodic meetings, and published guidance should be considered in choosing this value (Estes and Frangopol, 2003). It is assumed that the 5% inspector error is equally distributed on the high and low sides.

When an inspector assigns a condition state, there is a range of values that can be quite large. To be conservative, it is assumed that the mean value of the CI is at the center of the range when the condition state is first identified. If the condition state range is from 70 – 84, for example, the mean value would be CI=77 at the first inspection in which the structure enters that condition state, as shown in Figure 4.1. Based on the assumed inspector qualifications, the probability of obtaining a value of CI<84 when the structure is actually in this condition state is 97.5%, or 0.975. The standard deviation σ can be computed as:

$$P(CI \leq 84) = 0.975 = \Phi(\frac{CI - \mu}{\sigma}) = \Phi(\frac{84 - 77}{\sigma})$$
$$\sigma = \frac{(84 - 77)}{\Phi^{-1}(0.975)} = \frac{(84 - 77)}{1.96} = 3.57 \tag{4.2}$$

where Φ is the standard normal variate whose value can be found in the standard normal distribution tables, and μ is the mean value of the condition state (Ang and Tang 1975).

The structure is assumed to transition linearly through the condition state. The design life of the structure initially dictates how long a structure is expected to remain in a specific condition state. The mean value will shift linearly toward the lower end of the condition state over time (see Figure 4.1). The standard deviation remains unchanged. If a structure remains in a condition state longer than anticipated, the mean value of the CI will remain at the lowest possible value in the condition state until an inspection reveals that the structure has entered a different condition state. In the example above, the mean value would remain at CI=70. Greimann et al. (1990) attempted to model CI deterioration using an exponential function, and Ayyub et al. (1996) modeled it on the basis of the sparse data collected. If the linear assumption is not correct, the actual inspection data will allow the model to be updated to reflect actual structural behavior, as will be shown with an example in this chapter. In the absence of any data, a linear CI deterioration assumption seems reasonable.

4.3 Failure

Failure occurs when a structure no longer performs as intended. It is assumed that failure is associated with the need for some sort of repair, rehabilitation or reconstruction. Therefore any modifications or adjustments to the failure definition can be based on the historical record of repair actions. The initial assumption of $CI_{failure}$ is N[25, 12.5], which indicates a normally distributed variable with a mean value of *CI=25* and a standard deviation of σ*=12.5*. The assumption is based on the CI definition shown in Table 2.2 (Chapter 2), where the CI range of 0 – 40 initiates replacement. From the description, it appears that a small number of repairs might occur in the 40 – 54 range, where there is moderate deterioration. Similarly, in most cases a responsible manager will not wait until a structure no longer functions (CI range 0 – 9) to make a repair. Greimann et al. (1990) used CI=40 to indicate a potentially hazardous situation when developing a CI methodology for miter gates. Figure 4.2 shows the $CI_{failure}$ distribution and the assumed percentage of replacements that would occur within the CI ranges. Those values are used for quantification of failure throughout this study.

4.4 System Condition Index

Higher-level CIs for subsystems, systems, and entire structures will also be probabilistic. Figure 4.3 shows the simplest possible series system and parallel system, each consisting of two components, A and B. Component A has CI_{actual} = N[85, 5] with an importance factor I=0.3, while component B has CI_{actual} = N[45, 20] with an importance factor I=0.7. For both of these systems, the mean value of the CI_{system} is computed using equation 3.1 (Chapter 3) as

$$CI_{System} = \sum_{j=1}^{n} I_j CI_j = I_A CI_A + I_B CI_B = (0.3)(85) + (0.7)(45) = 57 \qquad (4.3)$$

Because the equation is linear and the variables CI_A and CI_B are independent and normal variates, the standard deviation of the system CI, $\sigma_{CI\ system}$ is (Ang and Tang 1975)

$$\sigma_{CI_{System}} = \sqrt{\sum_{j=1}^{n} I_j^2 \sigma_j^2} = \sqrt{I_A^2 \sigma_A^2 + I_B^2 \sigma_B^2} = \sqrt{(0.3)^2 (5)^2 + (0.7)^2 (20)^2} = 14.08 \qquad (4.4)$$

These equations provide the probabilistic parameters of the CI at successively higher levels.

4.5 Example Structure

The methodology is illustrated on a simple hypothetical structure shown in Figure 4.4. The structure consists of three parallel components (A1, A2, and A3) in series with components B and C. The components (in blue or light gray) are inspected and given a CI rating based on condition tables. Components A1, A2, and A3 form subsystem A. The structure consists of subsystem A and components B and C. The importance factors at each level are shown in Figure 4.4b.

Figure 4.5 shows the condition tables and the distributions they represent for components A1, A2, and A3. The condition evaluation for these components was divided into four condition states (CS) with ranges as indicated. The condition index range for CS1 was 70 – 100, which indicates a mean value of CI = 85 when the condition state is first entered. The standard deviation for CS1 using equation 4.2 is

$$\sigma_{CS1} = \frac{(100-85)}{\Phi^{-1}(0.975)} = \frac{(100-85)}{1.96} = 7.65 \qquad (4.5)$$

The parameters for the other condition states were computed in a similar manner. The distributions for the four condition states when the condition states are first entered are shown in Figure 4.5b along with the distribution for failure. The probability of failure of a component will be the likelihood that the actual CI is less than the defined failure CI. Figure 4.6 and Figure 4.7 show the condition tables and the resulting distributions for components B and C, respectively. Component B was divided into seven condition states while component C had only three. The analysis will be most effective when a component can be divided into more discrete, clearly defined categories, but that is clearly not possible for all components.

4.6 CI Over Time

The structure and its components are assumed to have a 50-year design life. With a linear transition within condition states, the structure should reach the zone 2 / zone 3 boundary line (*CI =40*) after 50 years (see Table 2.2, Chapter 2). The components A1 (with components A2 and A3 behaving the same way), B, and C should pass through CS 1.67, 4, and 1.33, respectively, during this period based on the condition tables in Figure 4.5 through Figure 4.7. Figure 4.8 illustrates the predicted condition state transition for components A1, B, and C based on the defined condition states for each component and assuming that the structure is inspected every 2 years. The data points are the mean CI values at points in time. Components A1 and C show a steep drop from CS1 to CS2 during the first 50 years of design life. Component B, which has seven defined condition states, shows more gentle drops as the component passes from CS1 – CS4 during the same period. The drop to the next condition state is triggered by an inspection where the inspector finds that the condition has changed.

Based on the assumed CS transition, the general equation for computing the mean CI for a component at Year X is:

$$CI_{YearX} = \max \left| \begin{array}{l} CI_{mid} - \dfrac{(CI_{mid} - CI_{\min})X}{(\frac{DLife}{\#CS} - 1)} \\ CI_{\min} \end{array} \right. \qquad (4.6)$$

Where CI_{mid} is the condition index at the midpoint of the condition state, CI_{min} is the lowest condition index in the condition state, *DLife* is the intended design life of the structure, *#CS* is the number of condition states that the structure will transition through as it moves from CI =100 to CI=40. Equation 4.6 shows that the CI_{YearX} value cannot fall below CI_{min}, until an inspection rating indicates that the structure is in a lower condition state. Using Equation 4.6, the mean CI for component A at years 2 and 4 is equal to

$$CI_{A,Year2} = 85 - \frac{(85-70)(2)}{(\frac{50}{1.67} - 1)} = 84.0 \qquad CI_{A,Year4} = 85 - \frac{(85-70)(4)}{(\frac{50}{1.67} - 1)} = 82.9$$

and the mean CI for component B at year 2 is

$$CI_{B,Year2} = 92.5 - \frac{(92.5-85)(2)}{(\frac{50}{4} - 1)} = 91.2 \qquad (4.7)$$

The CS transition proceeds in this manner until the component passes to the next-lower condition state, where the mean CI is the midpoint of the new condition state.

The mean CI of the entire structure is computed using equation 2.1 for a series system. Because components A1, A2, and A3 are identical in their performance, the mean CI for subsystem A is identical to its components. At t=0 years, when the structure is first placed into service, the mean value and standard deviation of the system structure are (from Chapter 3, equation 3.1):

$$\begin{aligned} CI_{System,Year0} &= (0.2)(85) + (0.6)(92.5) + (0.2)(85) = 89.5 \\ \sigma_{System,Year0} &= \sqrt{(0.2)^2(7.65)^2 + (0.6)^2(3.83)^2 + (0.2)^2(7.65)^2} = 3.16 \end{aligned} \tag{4.8}$$

By year 2, the mean value of the system is shown below and the standard deviation does not change.

$$CI_{System,Year2} = (0.2)(84.0) + (0.6)(91.2) + (0.2)(84.2) = 88.3 \tag{4.9}$$

The mean value of the system CI is also shown in Figure 4.8. The system CI follows closely with component B because the importance factor was 0.6 for that component, which was weighted three times as great as the other two components. If the importance factors changed, the system CI curve would reflect that.

4.7 Risk Analysis Using Condition Indices

Because the CIs have been defined in probabilistic terms, a risk analysis is possible relative to the CI definition of failure. Because the variables are normally distributed and independent, the reliability index is computed using equation 2.4. The reliability index for component A1 and for the system at year 2, for example, is computed as:

$$\begin{aligned} \beta_{A1,Year2} &= \frac{CI_{Actual} - CI_{Failure}}{\sqrt{\sigma^2_{Actual} + \sigma^2_{Failure}}} = \frac{84 - 25}{\sqrt{(7.65)^2 + (12.5)^2}} = 3.96 \\ \beta_{System,Year2} &= \frac{88.3 - 25}{\sqrt{(3.16)^2 + (12.5)^2}} = 4.82 \end{aligned} \tag{4.10}$$

Figure 4.9 shows the reliability index β for components A1, B, and C and for the structure. Not surprisingly, the graphs look very similar to the mean CI values shown in Figure 4.8 over the same 70-year time period. Figure 4.10 shows the probability of failure over this period for the components and structure. The probability of failure for component A1 and the system at year 2 are computed using equation 2.5 (Chapter 2):

$$p_{f,A,Year2} = \Phi(-\beta) = \Phi(-3.96) = 1 - \Phi(3.96) = 1 - 0.999963 = 3.7(10)^{-5}$$
$$p_{f,System,Year2} = \Phi(-4.82) = 7.15(10)^{-7} \tag{4.11}$$

The system probability of failure is fit to a Weibull distribution to provide a smooth curve. The hazard function is obtained using equation 2.8. Figure 4.10 shows for example that the probabilities of failure of the system for years 40, 42, and 44 are:

$$p_{f,System,Year40} = 0.1076 \qquad p_{f,System,Year42} = 0.1263 \qquad p_{f,System,Year44} = 0.1473 \tag{4.12}$$

Using equation 2.3, the probability of survival is:

$$p_{s,System,Year40} = 1 - 0.1076 = 0.8924 \quad p_{s,System,Year42} = 0.8737 \quad p_{s,System,Year44} = 0.8527 \tag{4.13}$$

The hazard functions for years 42 and 44 are computed using equation 2.8 (Chapter 2) as:

$$\begin{aligned}
f(t)_{System,Year42} &= \frac{dF_T}{dt} = \frac{(0.1263 - 0.1075)}{42 - 40} = 0.009389 \\
H(t)_{System,Year42} &= \frac{f(t)}{p_s(t)} = \frac{f(42)}{p_s(42)} = \frac{0.009389}{0.8737} = 0.01075 \\
f(t)_{System,Year44} &= \frac{(0.1473 - 0.1263)}{44 - 42} = 0.01047 \\
H(t)_{System,Year44} &= \frac{f(44)}{p_s(44)} = \frac{0.01047}{0.8527} = 0.01228
\end{aligned} \tag{4.14}$$

This indicates that if the structure has not already failed by year 42, the likelihood of the structure needing replacement in the next year is 0.01075. Figure 4.11 shows the hazard function for the system over a 70-year period. Because the probability of failure jumps when condition states change, the hazard curve is not smooth and shows spikes. Using real data, the numerical differentiation will almost never produce a smooth curve. A best-fit Weibull distribution is fit through the data. The Weibull distribution requires two-parameters, γ and θ, such that best-fit hazard function through the data is expressed as (Padula et al. 1994):

$$h(t) = \frac{\gamma}{\theta}(\frac{t}{\theta})^{\gamma-1} \qquad (4.15)$$

The parameters are estimated through linear regression analysis. The data for time t and reliability p_s over the 76-year period are converted to x and y data using the equations:

$$\begin{aligned} x_{Year42} &= \ln(t) = \ln(42) = 3.738 \\ y_{Year42} &= \ln(\ln\frac{1}{p_s}) = \ln(\ln(\frac{1}{0.8737})) = -2.002 \end{aligned} \qquad (4.16)$$

The x-y data are fitted to the linear equation

$$y = ax + b \qquad (4.17)$$

Using the data for the 70-year period, regression analysis showed that a=*-22.67* and b=*5.483*. The parameters γ and θ are computed as:

$$\begin{aligned} \gamma &= b = 5.483 \\ \theta &= \frac{1}{e^{(\frac{a}{b})}} = \frac{1}{e^{(\frac{-22.67}{5.483})}} = 62.50 \end{aligned} \qquad (4.18)$$

Using equation 4.15, the hazard functions for the best-fit curve for years 42 and 44 are:

$$\begin{aligned} h(t)_{Weibull,year42} &= \frac{5.483}{62.5}(\frac{42}{62.5})^{(5.483-1)} = 0.01477 \\ h(t)_{Weibell,year44} &= \frac{5.483}{62.5}(\frac{44}{62.5})^{(5.483-1)} = 0.01819 \end{aligned} \qquad (4.19)$$

Figure 4.11 shows the best-fit hazard function for the entire time period.

The failure consequences of the structure illustrated in Figure 4.4 are shown in Figure 4.12. A failure consequence analysis for this hypothetical structure indicates that there is a 50% chance that if the structure fails, the consequences would be slight and the cost would be only $100,000. At the other extreme, there is a 2% chance that the failure would be catastrophic and cost would be $110 million. The expected cost of failure based on the event tree is:

$$E(Cost)_{failure} = (0.50)(\$100{,}000) + (0.25)(\$400{,}000) + (0.15)(\$2{,}000{,}000) + (0.08)(\$25{,}000{,}000) + (0.02)(\$110{,}000{,}000) = \$4{,}650{,}000 \tag{4.20}$$

At year 42, the expected annual cost of keeping the structure in service, assuming no maintenance cost, is

$$E(Cost)_{Year42} = \$4{,}650{,}000(0.01477) + \$0(1 - 0.01477) = \$68{,}680 \tag{4.21}$$

There is obviously some failure cost associated with the new structure. In this case, the hazard function for year 1 of this structure was $1.74(10)^{-8}$, which makes the failure cost slightly less than eight cents — a negligible consideration. The present value cost, C_{pv} of a new structure at year 42 is \$2,000,000 with an anticipated design life of 50 years. Assuming a discount rate of 6%, the annual cost over the 50-year life is

$$C_{annual} = \frac{C_{pv} r(1+r)^n}{(1+r)^n - 1} = \frac{\$2{,}000{,}000(0.06)(1+0.06)^{50}}{(1+0.06)^{50} - 1} = \$126{,}890 \tag{4.22}$$

This result indicates that the new structure would not be justified at year 42 because the annual cost of \$126,890 exceeds the annual benefit of \$68,680 that would be provided by a new structure (Estes and Frangopol 2004).

Figure 4.8 through Figure 4.12 reflect the proposition that a risk-based cost/benefit analysis is possible using CI data. The inspection results in this example reflect a structure that performed as predicted and a case in which all of the assumptions are valid. It is acknowledged that the assumptions are not based on actual data, but as time passes and CI data for a structure become available through actual inspection, the original assumptions may be modified and the life-cycle maintenance plan can be updated. The advantage of the approach is that the data needed for the analysis are the same as the data being collected in the inspection.

4.8 Actual versus Expected Structural Performance

The next examples illustrate what occurs if the structure shown in Figure 4.4 does not behave as predicted or if the assumptions prove invalid. Figure 4.13 shows the results for the structure in Figure 4.4 when every component is deteriorating at twice the expected rate. The changes in CS for the components show a steeper drop than in Figure 4.8. The actual CI for the system is still a factor of the importance and condition state of its constituent components. Figure 4.13 compares the actual structure CI with the predicted structure CI over 40 years. The life of the actual structure will be 20 – 30 years rather than the design life of 50 years, but the inspection results show that within its first decade of service the structure is behaving differently than expected, so a revised life-cycle maintenance plan can be developed. The same risk analysis described earlier is conducted for the more rapidly deteriorating structure. Figure 4.14 shows the actual hazard function and best-fit Weibull hazard function for the more rapidly deteriorating structure.

Similarly, Figure 4.15 shows the results for a structure where every component is deteriorating at half the expected rate. The CI values for the components flatten out as the structure behaves better than expected and the mean CI remains at the lowest value in the CS until an inspector finds that it has deteriorated to the next-lower condition state. The actual structure CI is compared with the original prediction. The expected service life of the actual structure is about 75 years rather than 50. This trend is evident by year 20, so there is plenty of opportunity to defer repair and rehabilitation in favor of a higher-priority project. Figure 4.16 shows the actual data and best-fit hazard functions for the less-deteriorated structure.

Figure 4.17 overlays the three hazard functions from Figure 4.11, Figure 4.14, and Figure 4.16 for the original structure, the structure deteriorating at double the expected rate, and the structure exhibiting half the deterioration rate. If a cost/benefit analysis were conducted at year 30, the hazard function values, H(30), would be 0.00327, 0.0501, and 0.000179, respectively. The values all differ by an order of magnitude, which would make a huge difference in the economic analysis. This example underscores that even if the initial assumptions are substantially incorrect the periodic inspection and updating allow for significant correction over time.

4.9 Effect of Repairs Over Time

Figure 4.18 considers the case where components A1 and B are deteriorating at half the expected rate, A3 and C at double the expected rate, and A2 at the expected rate. The mean CI rating for the actual structure and the predicted structure are both shown. Component C completely fails at year 40, but the structure CI is only moderately affected because the importance factor of component C was only $I=0.2$ and Component B, which is performing better than expected, has an importance factor of *I=0.6*. At year 40, component C is replaced and its CI reflects the new condition by year 42. The CI of the system improves somewhat as a result, indicating a better condition of the overall structure. At year 46, the mean CI of subsystem A rises from 51 to 67, but not all the way back to its new condition of *CI = 85*.

Figure 4.19 shows the individual components A1, A2, and A3 of the parallel subsystem A. At year 46, component A3 needs to be replaced and its CI returns to its original value of CI=85. Because components A1 and A2 are still performing well, they are not replaced. Thus, the CI of subsystem A improves, but not back to its original condition (i.e., the mean of the highest condition state) after the replacement of A3.

4.10 Alternative Approaches for System Analysis

The treatment of a structure as a system is controversial because strong arguments could be made for competing approaches.

4.10.1 Weighted Average Approach

The approach taken by Chouinard et al. (2003) and the study reported here treats the higher-level CI as the overall condition of the structure based on the component CIs and their relative importance. This approach allows entire structures competing for the same resources to be compared at a higher level. Returning to the automobile analogy (see section **Error! Reference source not found.**), if a manager has a fleet of cars, one car might be 10 years old, have experienced a series of electrical problems, and never had the brakes replaced. A second car is eight years old and is showing signs of body rust and a faltering transmission. A system CI would be helpful in assessing which car would benefit more from scarce maintenance dollars. The probabilistic analysis would help determine if either project could be justified economically.

4.10.2 Traditional Reliability Approach

A second approach would be to compute system reliability using equations 2.10 and 2.12 (Chapter 2) for series and parallel systems, respectively. This traditional reliability approach should produce a series system CI that would be lower than any of the component CIs. Similarly, the CI of a parallel system should be higher than any of the component CIs, which conflicts with equation 3.1.

For example, using the structure in Figure 4.4 and the probabilities of failure in Figure 4.10, the approaches are compared at year 0 and year 40 of structural life. Table 4.1 shows the probabilities of failure for the components at Year 0 and Year 40, as well as the failure probabilities for subsystem A and the overall system using the weighted average approach proposed herein. Subsystem A is a parallel system consisting of components A1, A2, and A3, which are all behaving in the same manner. If the components are independent using the traditional approach, the reliability of subsystem A at year 0 is determined using equation 2.12 (Chapter 2):

$$P_{f\,Sub-sys-A} = (0.0000275)(0.0000275)(0.0000275) = 2.07 * 10^{-14} \tag{4.23}$$

If the components are perfectly correlated, then the reliability is equal to the reliability of the strongest component, as expressed by

$$P_{f\,Sub-sys-A} = p_{f,\min} = 0.0000275 \tag{4.24}$$

Similarly, if the structure's components (subsystem A, components B and C) are independent, the reliability of the overall system at year 0 is determined by equation 2.10 (Chapter 2) for the series system as:

$$P_{f\,system} = 1 - [(1 - 2.07 * 10^{-14})(1 - 2.00 * 10^{-7})(1 - 0.0000275)] = 0.0000277 \tag{4.25}$$

If the components are perfectly correlated, then the reliability is equal to the reliability of the weakest component

$$P_{f\,system} = p_{f,\max} = 0.0000275 \tag{4.26}$$

Table 4.1 shows these results for both year 40 and year 0. There is a large difference between the results obtained using the currently proposed weighted average method and the traditional reliability approach, even on this small hypothetical structure, because the two approaches measure different things. Because most structures are series systems, the traditional reliability approach — whether one is looking at statistical independence or perfect correlation — reflects the probability of anything, however small, going wrong. In the automobile analogy (section **Error! Reference source not found.**), the failed component might be a dead battery, a flat tire, or a seized engine. As parts of a series system, any of those component failures would cause the system to fail and require some action to be taken before the automobile could be safely operated again. Using the traditional reliability approach for the system there is no way to account for the importance of components: a dead battery would be viewed with the same degree of seriousness as a seized engine. In this simple example, there was not a big difference between the results when considering independence versus perfect correlation. For a seven-level hierarchy the difference would be more pronounced, however, and considering the correlation between components would become more important.

The weighted-average CI method measures the likelihood of replacing or overhauling the entire system. It allows two similar systems with different distresses to be compared in terms of allocation of scarce maintenance resources. The importance each component is fully considered in the analysis; a dead auto battery would have such minor importance that the automobile's system CI would be negligibly affected by it. This approach intuitively makes sense: no reasonable owner would replace or rehabilitate an automobile due to a dead battery, but he or she would do so if the engine were seized.

The two approaches are different in what they are attempting to measure and would almost never produce the same answer. In the traditional approach, the probability of failure in a series system will always be at least as high as that of its weakest member. The probability of failure in a parallel system will always be as low as or lower than that of its strongest member. Using the weighted-average approach advocated in this report, the probability of system failure will always lie somewhere between the failure probability of its strongest and weakest components.

Because equation 3.1 conflicts with traditional reliability analysis, a final issue to address is to describe how a system CI value would be computed using the traditional reliability approach. The system CI would need to be developed by using the mean and standard deviations of the component CIs to compute failure probabilities of the individual components. Those individual probabilities are used to determine the system probability of failure, which is then converted to a system CI value. Using Figure 4.8 and Table 4.1 as an example, the CI values for the components A1, B, and C at year 40 are A1[39.4, 11.22], B[45.8, 3.57], and C[30.8, 11.22]. The mean CI values for subsystem A and the entire structure at year 40 are 39.4 and 41.4, respectively, using the weighted average approach. From Table 4.1, the probability of subsystem A failure at year 40 using the traditional reliability method for a parallel system assuming, statistical independence, is $p_f = 0.0078$. The reliability index β for subsystem A would be

$$\beta = \Phi^{-1}(p_f) = \Phi^{-1}(0.0078) = 2.42 \tag{4.27}$$

Using a standard deviation value of $\sigma_{CI} = 11.22$ for subsystem A and equation 4.10, the system CI is computed as:

$$CI_{Actual,Sub-SystemA} = \beta\sqrt{\sigma^2_{Actual} + \sigma^2_{Failure}} + CI_{Failure} = 2.42\sqrt{(11.22)^2 + (12.5)^2} + 25 = 65.6 \tag{4.28}$$

As expected, the CI of the parallel system is greater than the CI of any of its components and much higher than the CI produced by the weighted average approach (*CI = 39.4*).

Also from Table 4.1, the probability of failure of the entire system at year 40 using the traditional reliability method for a series system assuming statistical independence is $p_f = 0.4081$. The reliability index β for the structure would be

$$\beta = \Phi^{-1}(p_f) = \Phi^{-1}(0.4081) = 0.23 \tag{4.29}$$

The components that comprise the system have different standard deviations. Using a standard deviation value of $\sigma_{CI} = 3.57$ for the structure and equation 4.10, the system CI is computed as:

$$CI_{Actual,Structure} = \beta\sqrt{\sigma^2_{Actual} + \sigma^2_{Failure}} + CI_{Failure} = 0.23\sqrt{(3.57)^2 + (12.5)^2} + 25 = 28.0 \tag{4.30}$$

Using a weighted average standard deviation and a standard deviation of 11.52 for the structure produced system CI values of 28.3 and 28.9, respectively. Again as expected, the CI of the series system is lower than the CI of any of its components and lower than the CI produced by the weighted average approach (*CI = 41.4*).

4.10.3 Other Considerations

It can be argued that that any CI value assigned above component level is misleading and should not be used. Foltz, Howdyshell, and McKay (2001) acknowledge that there is considerable disagreement on the need for system or summary condition indices. Those who oppose using a summary index are inclined to support using CI data for reliability assessment and would favor the traditional reliability approach over the weighted average approach proposed here. A properly developed system CI would provide valuable summary information in a standardized context on the condition of an entire class of structures. Such information provides a systematic and credible tool for describing the state of the infrastructure for setting maintenance priorities in order to most effectively avoid economic losses and safety hazards. Also, as compared with traditional reliability analysis, it is the only feasible way to evaluate entire dissimilar structures from the common frame of reference that planners and managers need to set repair and rehabilitation priorities.

The example problem (section 4.5) illustrates another argument against using higher-level CI ratings for structures. Using that approach it would be easy to neglect a minor component that must be repaired or replaced for the structure to function. If a failing component has a small importance factor and other components are performing better than expected, the small failure may be missed by an analyst focusing on a structure-level CI. Returning again to the automobile analogy, even though no one would justify a major rehabilitation or replacement just because the car battery is dead, the system will not operate without a functional battery. Consequently, a system based on the weighted-average approach needs to show a ‘red flag’ whenever any component CI mean value rating falls below 40 and a deliberate decision to repair or not repair is needed.

4.11 Summary

This chapter has explained a methodology for using CI ratings based on visual inspection results to perform a type of risk-based analysis of a structure. The approach was illustrated on a hypothetical series-parallel structure. Through a variety of assumptions, failure and condition state randomness were defined, component and system CIs were computed, and a cost/benefit analysis involving the reliability index, probability of failure and hazard function was performed. The example problem demonstrated how these assumptions can be updated and modified over time as actual inspection data become available. The issues associated with system level CIs were discussed. With the methodology demonstrated on a small hypothetical structure, the next chapter will address a complex, real-world structure used by Chouinard et al. (2003).

Table 4.1. Comparison of proposed probabilistic system CI and the traditional system reliability approach for both statistically independent and perfectly correlated components.

Year 0				
Item	**Probability of Failure**			
	Component	**System: Weighted Average Approach**	**System: Traditional Approach Statistical Independence**	**System: Traditional Approach Perfect Correlation**
Component A1, A2, A3	2.75E-05			
Component B	2.00E-07			
Component C	2.75E-05			
Subsystem A		2.75E-05	2.07E-14	2.75E-05
Structural System		4.59E-07	2.77E-05	2.75E-05
Year 40				
Item	**Probability of Failure**			
	Component	**System: Weighted Average Approach**	**System: Traditional Approach Statistical Independence**	**System: Traditional Approach Perfect Correlation**
Component A1, A2, A3	0.1984			
Component B	0.0583			
Component C	0.3665			
Subsystem A		0.1984	0.0078	0.1984
Structural System		0.1076	0.4081	0.3665
Note: Components A1, A2, and A3 are all behaving in the same manner and thus all have the same reliability.				

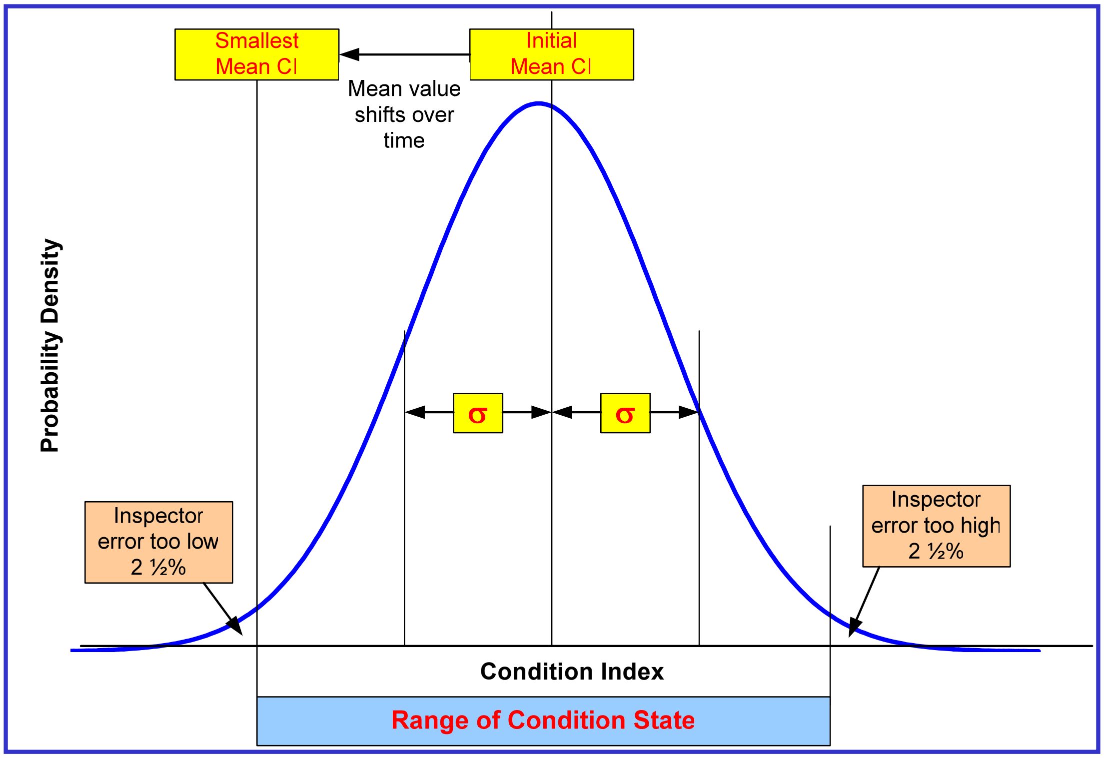


Figure 4.1. Typical condition state definition in probabilistic terms. The initial CI value is the mean value of the distribution, and the CI progressively shifts left over time.

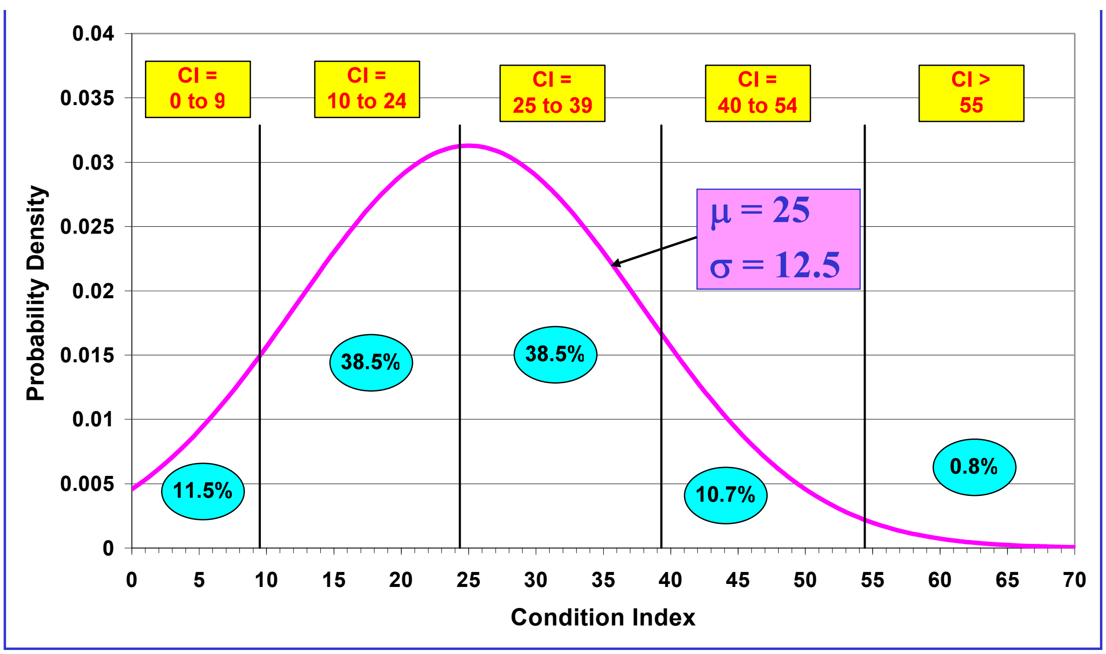


Figure 4.2. CI definition of failure expressed in probabilistic terms as a truncated normal distribution with a mean value of CI=25 and standard deviation of 12.5. The percentage of failures expected to occur in each range is shown.

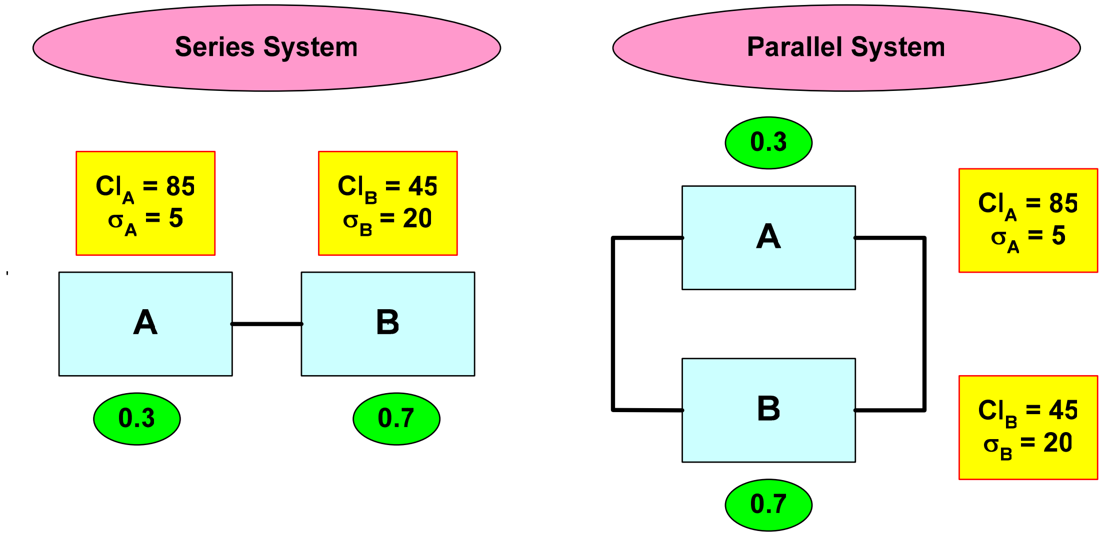
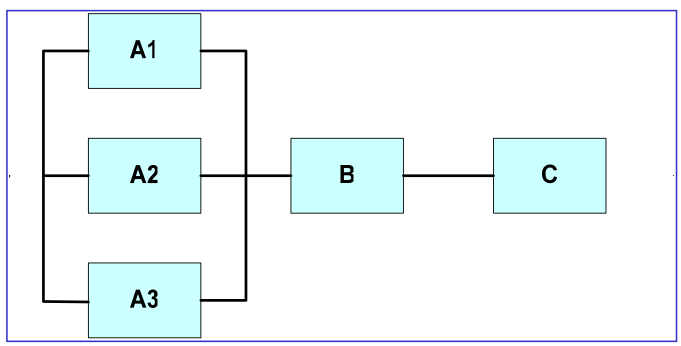


Figure 4.3. Simple series and parallel systems consisting of components A and B.

a.



b.

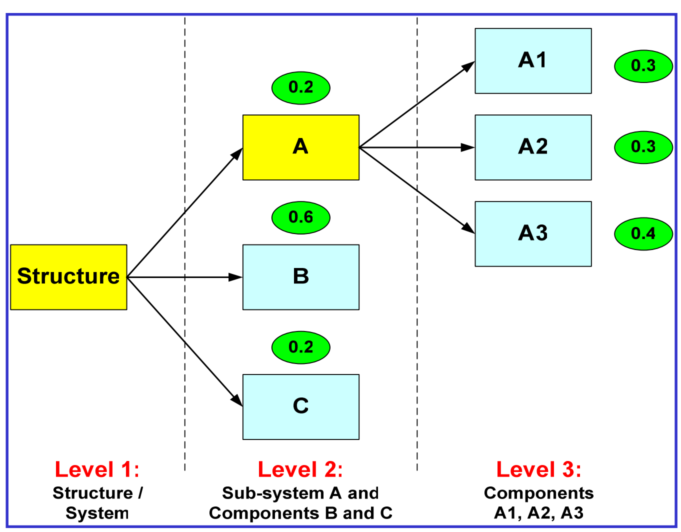


Figure 4.4. Hypothetical series-parallel structure (a) and structural hierarchy for hypothetical structure with importance factors assigned (b).

Components A1, A2, and A3									
Condition State	Condition Index Score							Mean Value	Standard Deviation
	0-9	10-24	25-39	40-54	55-69	70-84	85 - 100		
1						x	x	85	7.65
2			x	x	x			47	11.22
3		x						17	3.57
4	x							4.5	2.29

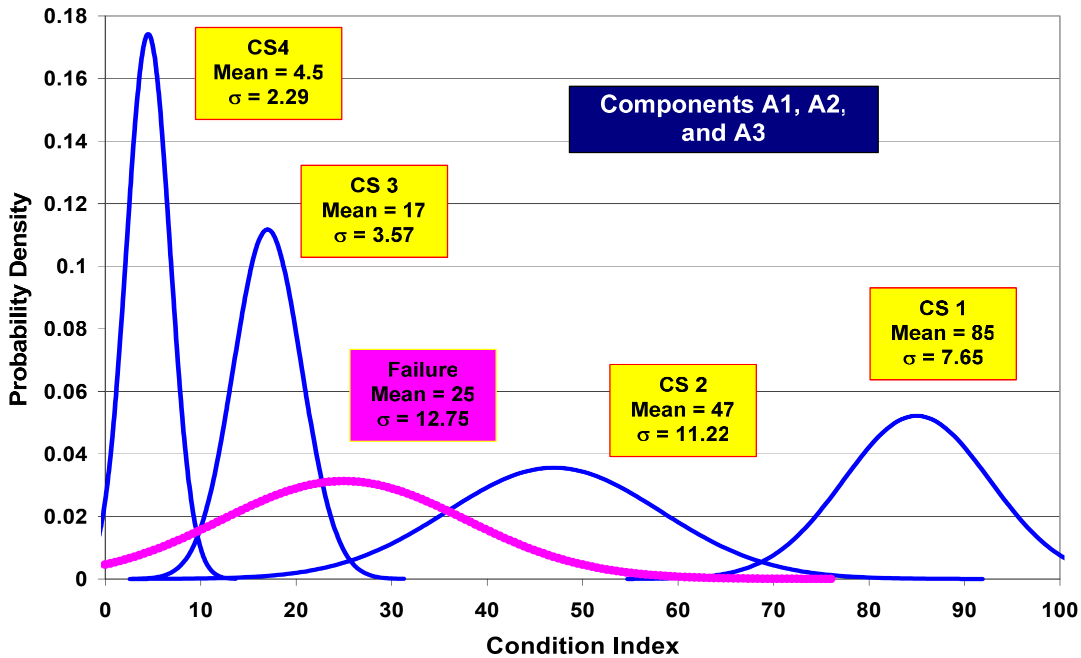


Figure 4.5. Condition table and probability distributions for components A1, A2, and A3.

Component B									
Condition State	Condition Index Score							Mean Value	Standard Deviation
	0-9	10-24	25-39	40-54	55-69	70-84	85 - 100		
1							x	92.5	3.82
2						x		77	3.57
3					x			62	3.57
4				x				47	3.57
5			x					32	3.57
6		x						17	3.57
7	x							4.5	2.29

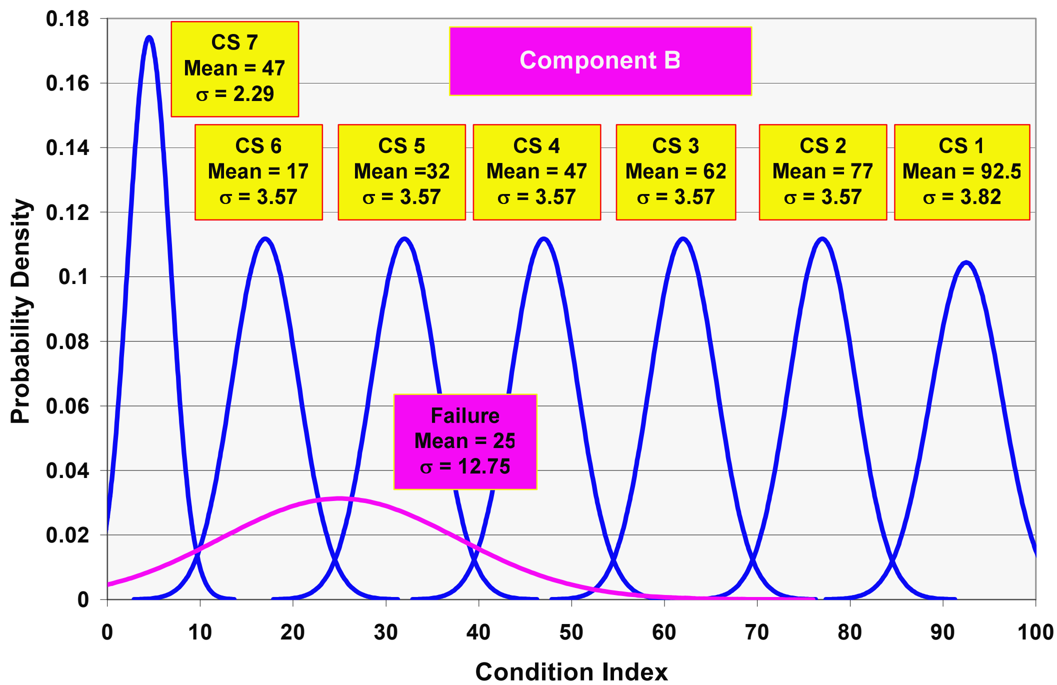


Figure 4.6. Condition table and probability distributions for component B.

Component C									
Condition State	Condition Index Score							Mean Value	Standard Deviation
	0-9	10-24	25-39	40-54	55-69	70-84	85 - 100		
1						x	x	85	7.65
2		x	x	x				32	11.22
3	x							4.5	2.29

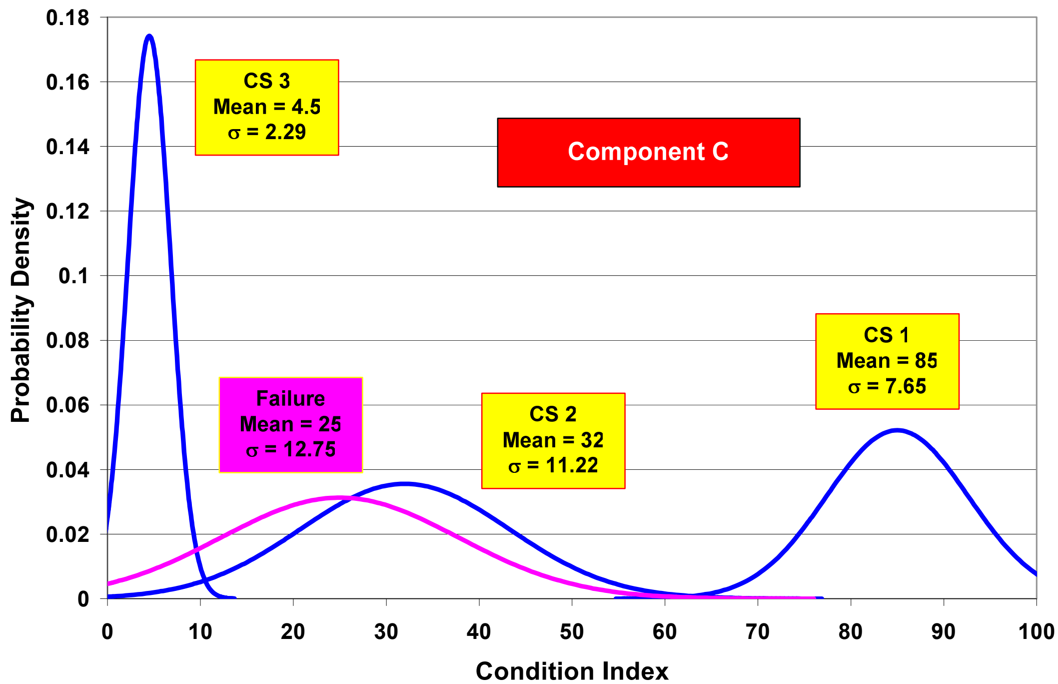


Figure 4.7. Condition table and probability distributions for component C.

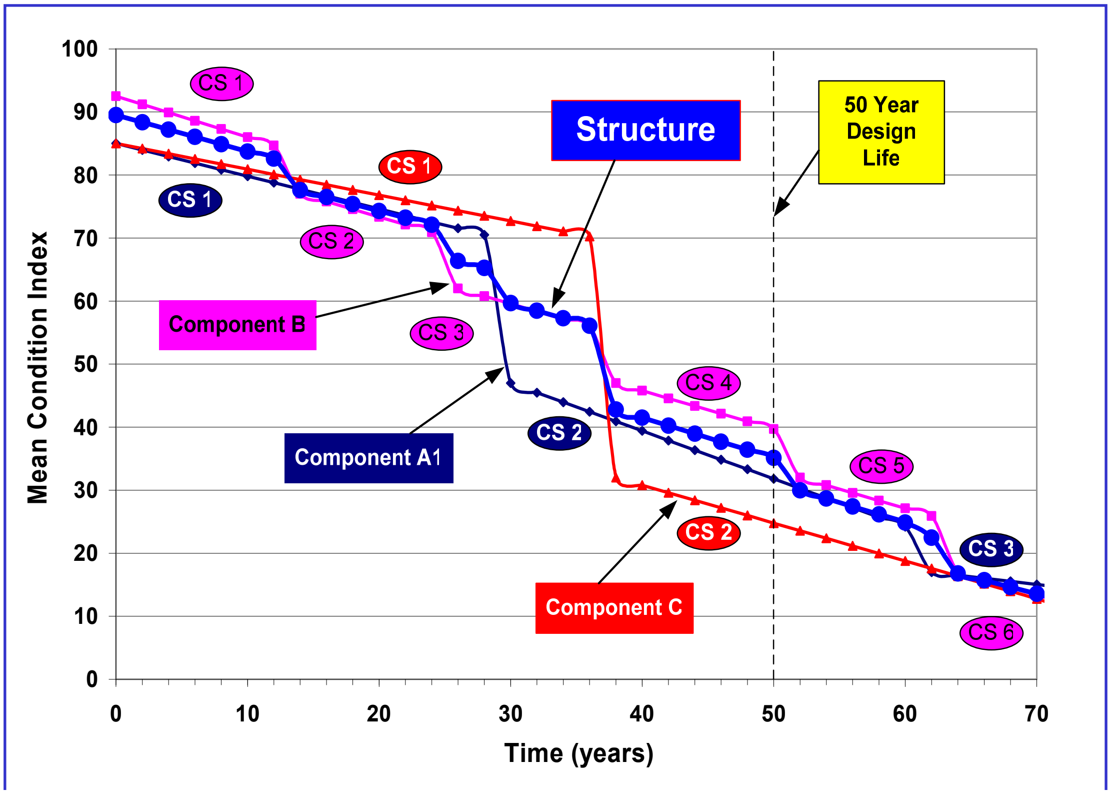


Figure 4.8. Expected condition state transition for the 50 year life of components A1, B, and C and the entire structure. Data points are the mean CI values at points in time.

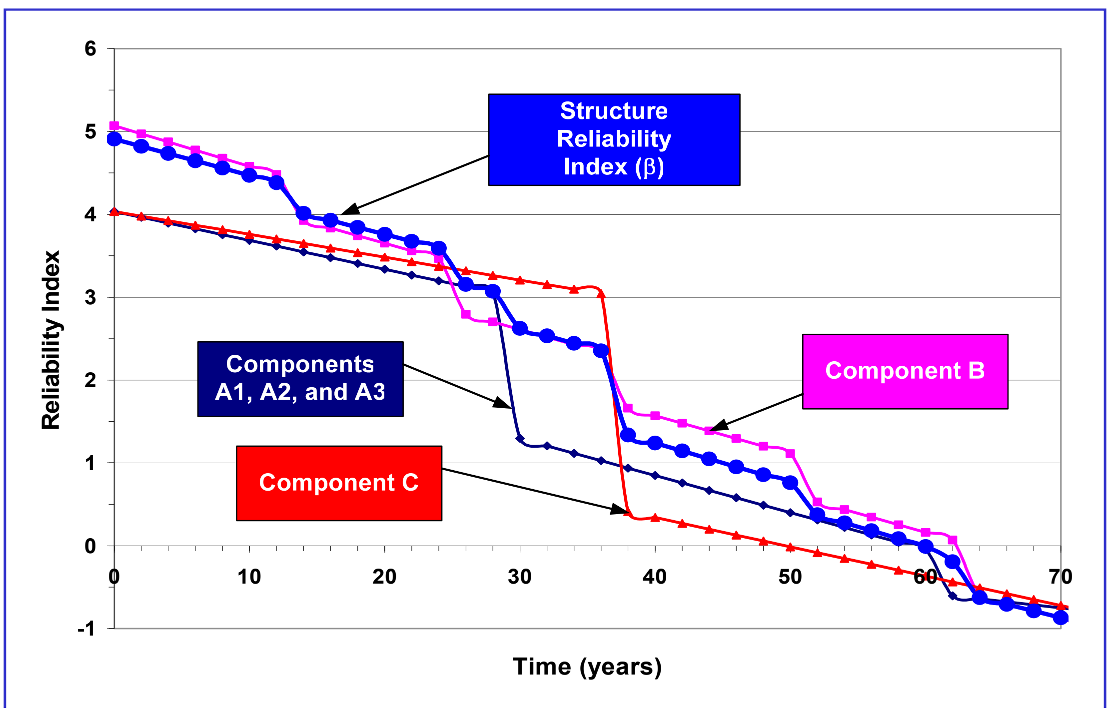


Figure 4.9. The reliability index (*β*) for components A1, B, and C and the entire structure over a 70-year period.

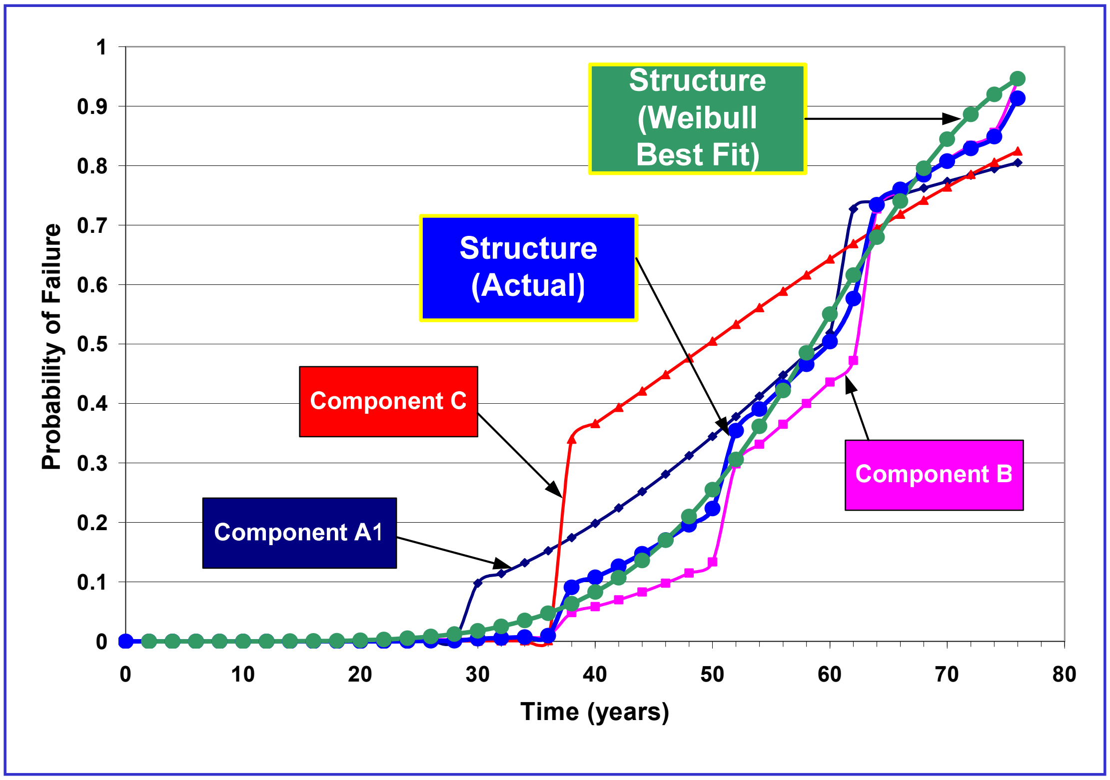


Figure 4.10. Failure probability for components A1, B, and C and the entire structure over a 75-year period.

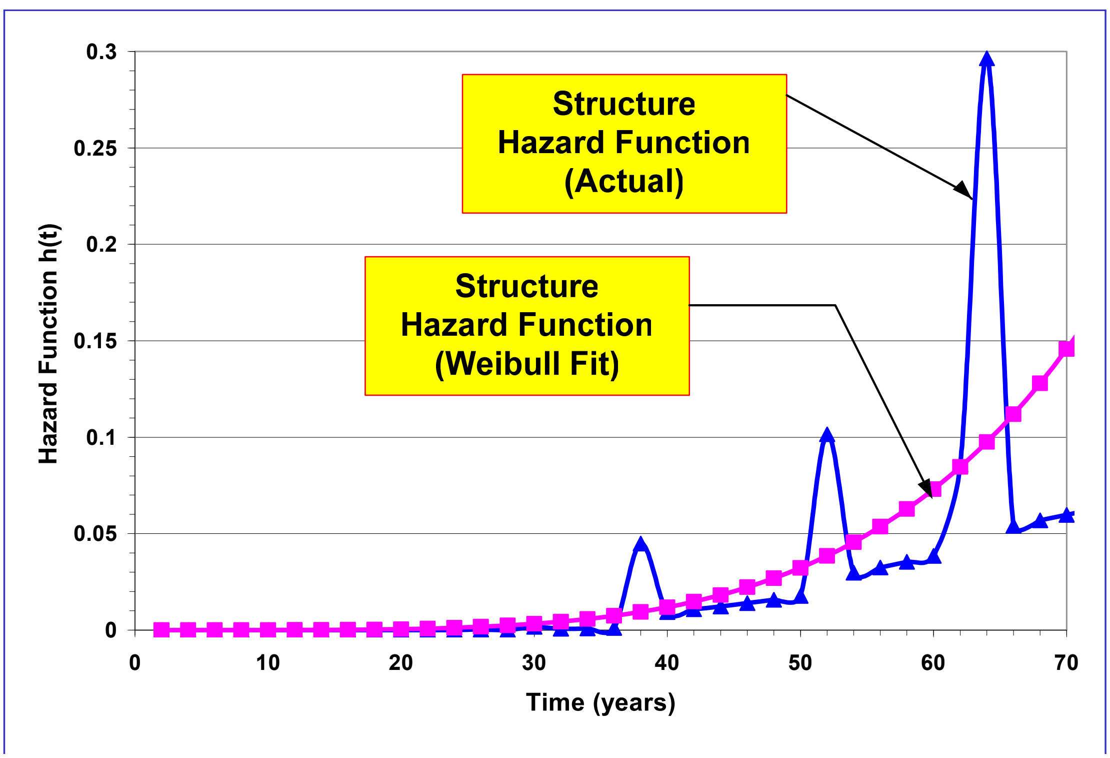


Figure 4.11. Hazard functions for a structure based on actual results and the best-fit Weibull distribution through the data.

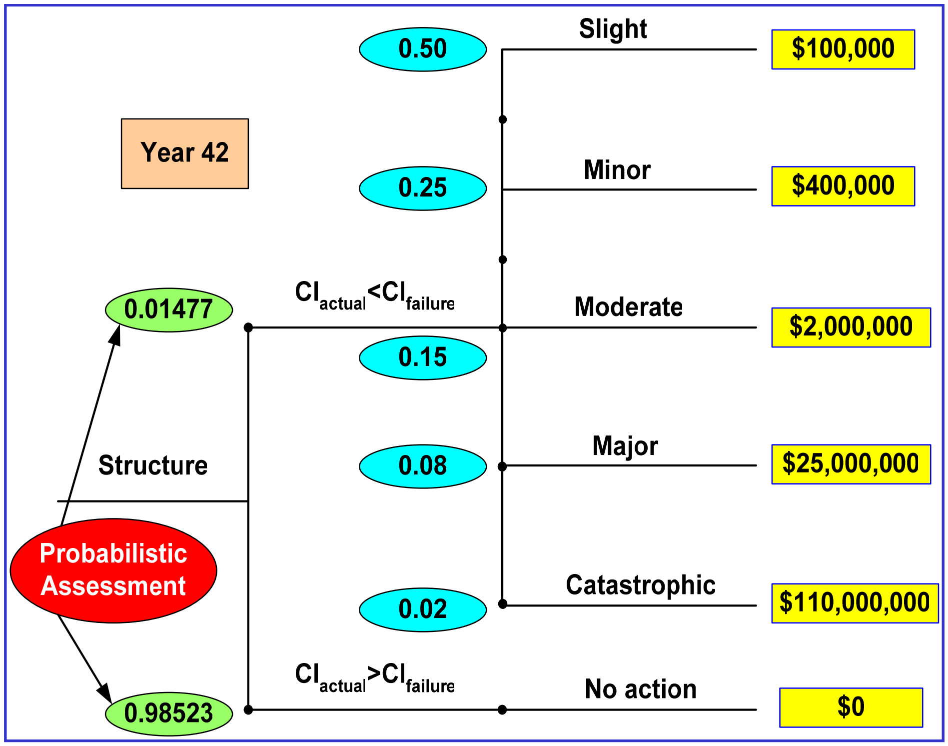


Figure 4.12. Cost failure tree for structure at year 42 of useful life based on consequences of failure and hazard function.

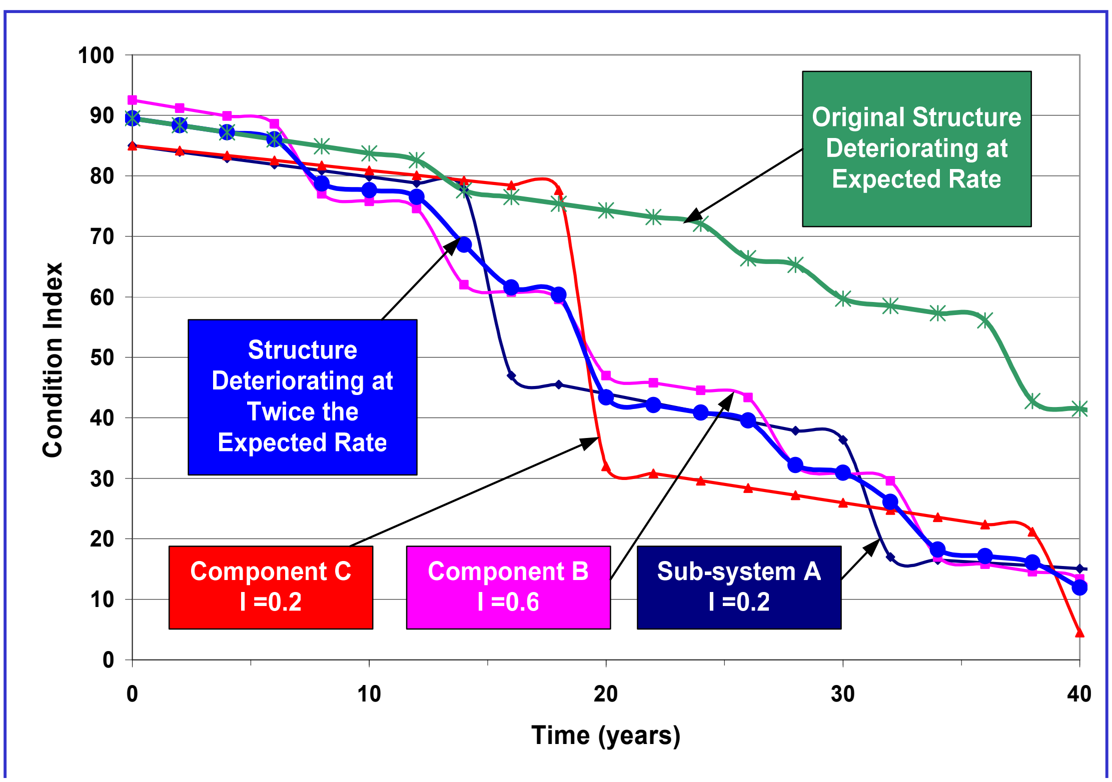


Figure 4.13. Mean CI for structure and its components deteriorating at double the predicted rate.

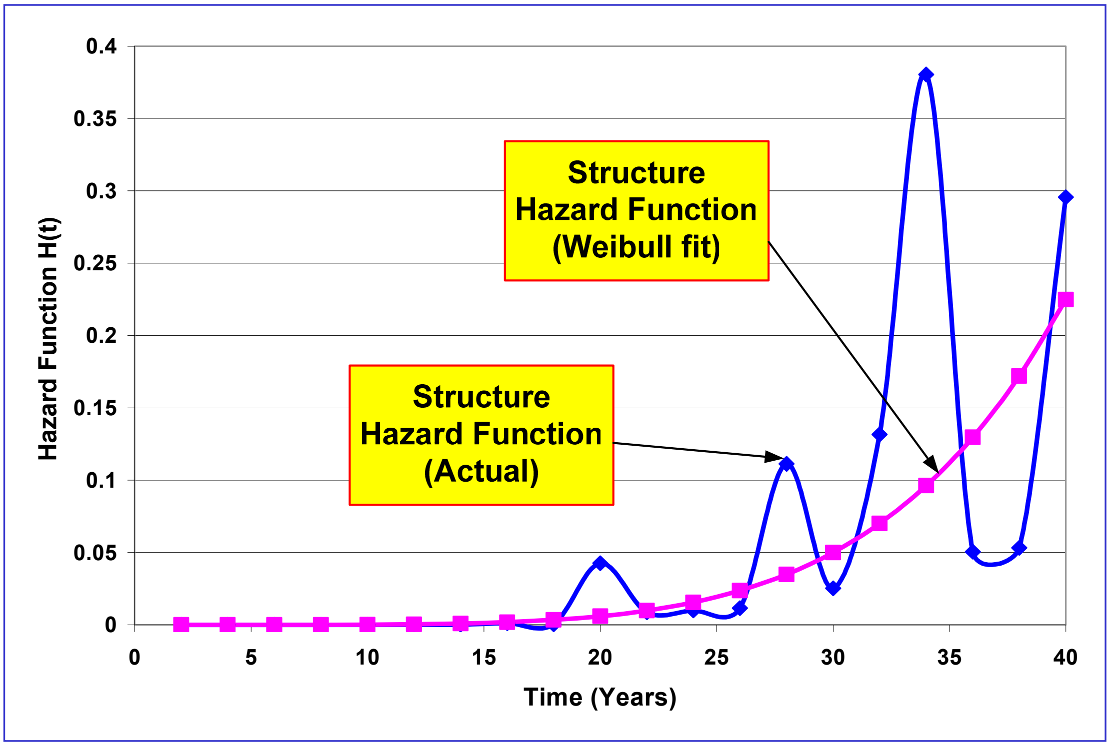


Figure 4.14. Hazard functions based on actual results and best-fit Weibull distribution through the data for structure deteriorating at twice the predicted rate.

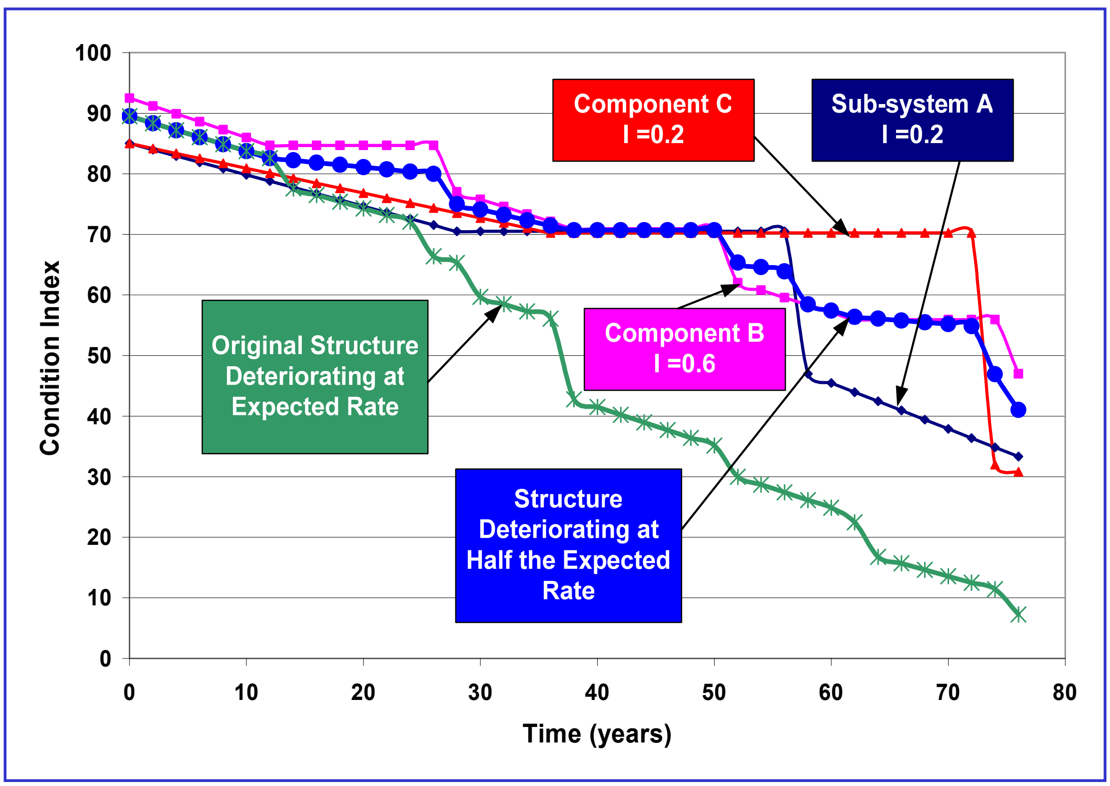


Figure 4.15. Mean CI for structure and components deteriorating at half the predicted rate.

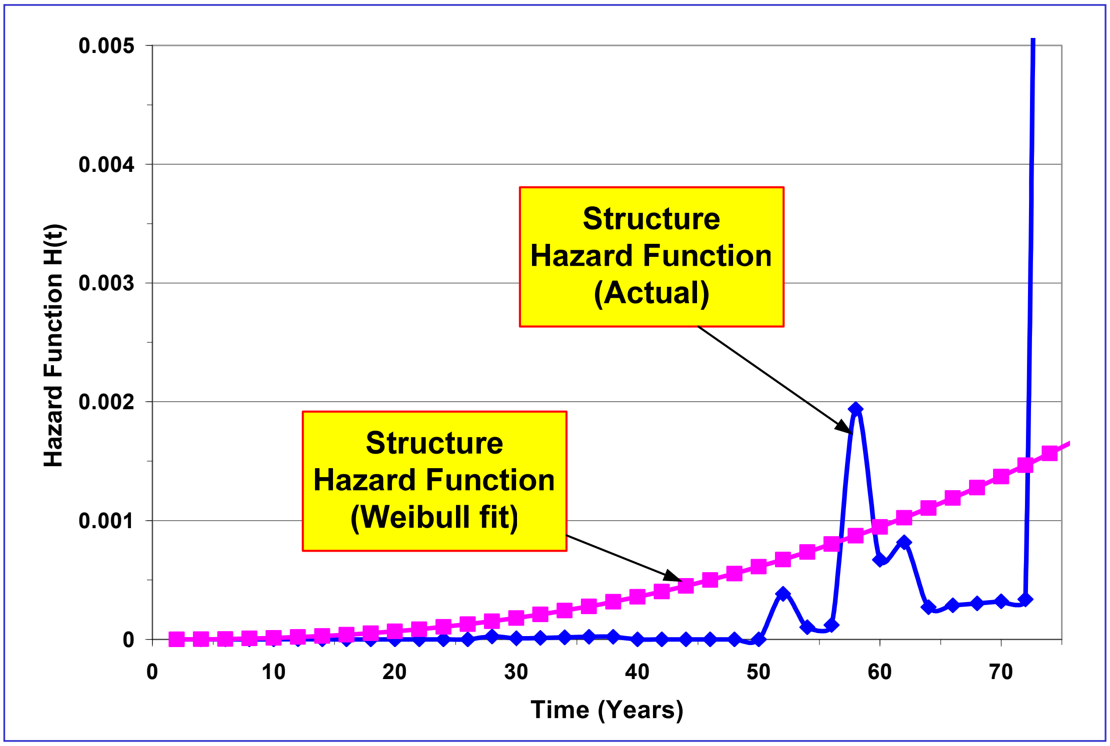


Figure 4.16. Hazard functions based on actual results and best-fit Weibull distribution through the data for structure deteriorating at half the predicted rate.

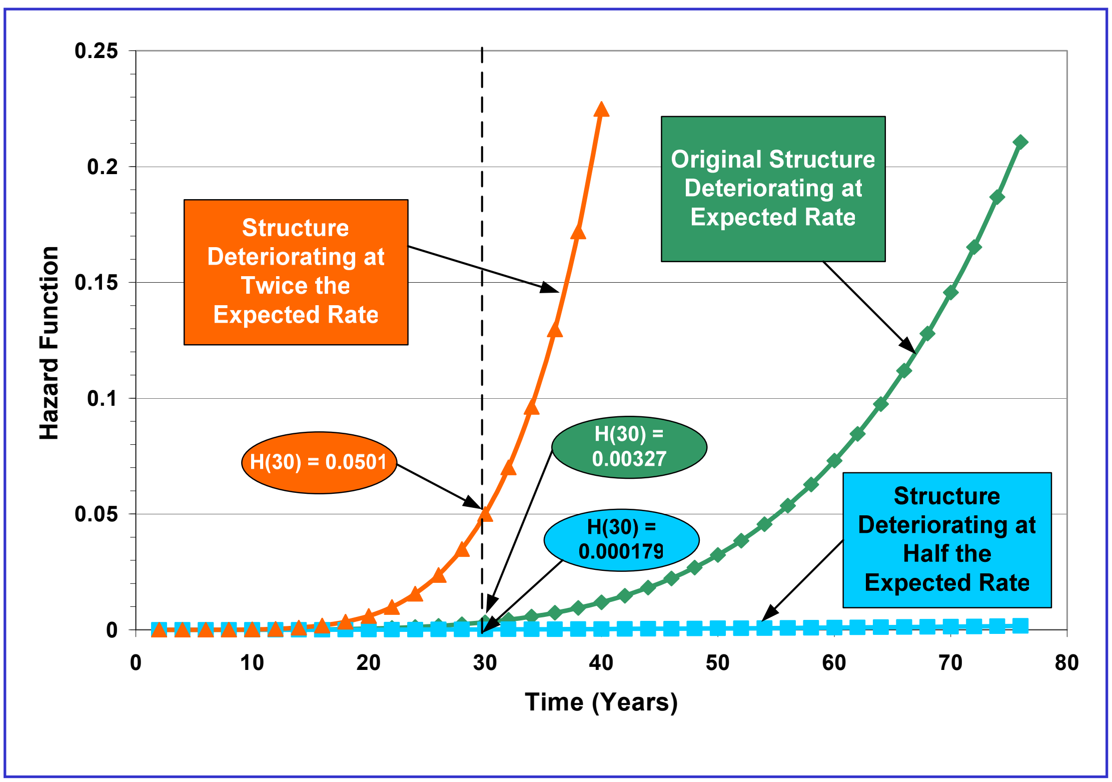


Figure 4.17. Hazard functions for structures deteriorating at predicted rate, twice the predicted rate, and double the predicted rate.

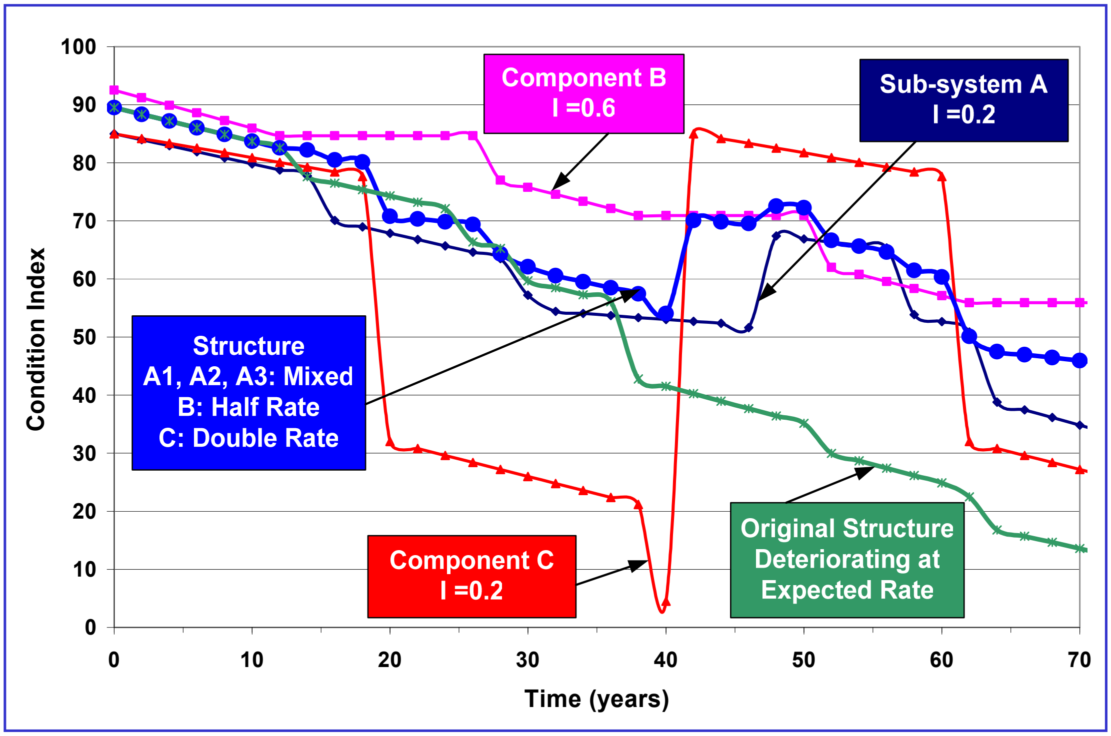


Figure 4.18. Mean CI for structure where components A1 and B are deteriorating at half the predicted rate and components A3 and C are deteriorating at double the predicted rate.

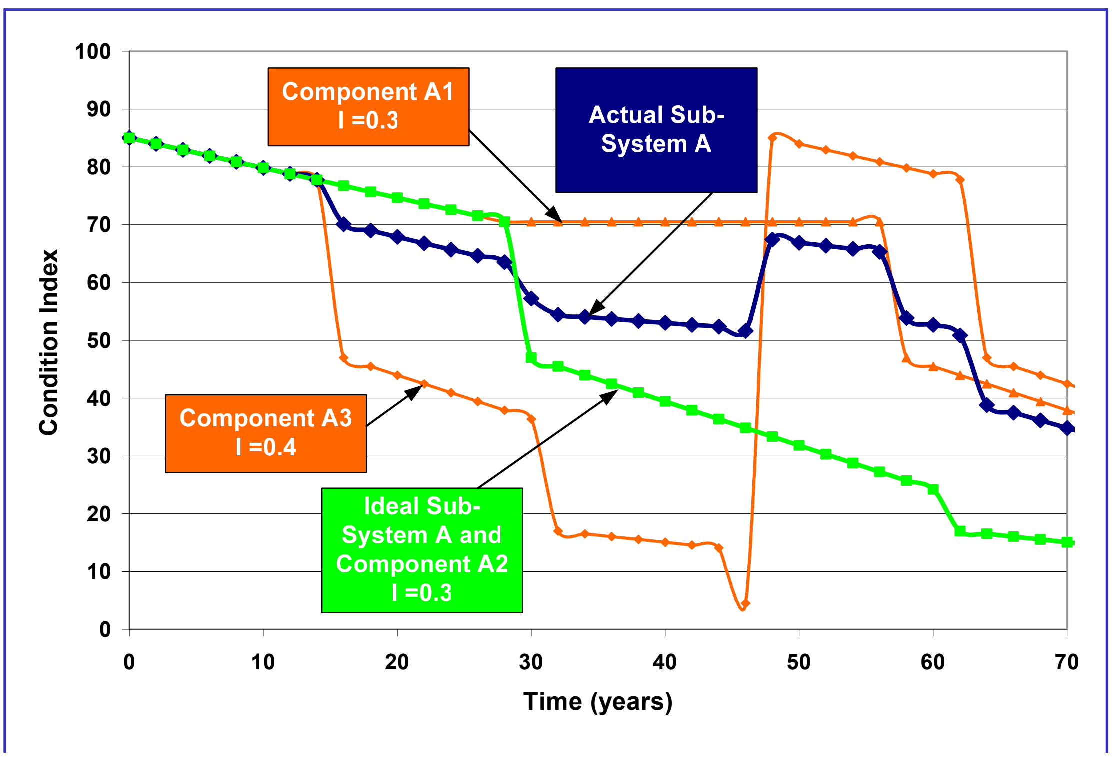


Figure 4.19. Mean CI for parallel system a where component A1 is deteriorating at half the predicted rate, component A3 is deteriorating at double the predicted rate, and Component A2 is deteriorating at the predicted rate.

5 Real-World Example Using the Great Falls Spillway

5.1 The Structural Hierarchy

The Great Falls dam shown in Figure 5.1 is one of six dams and power plants managed by Manitoba Hydro on the Winnipeg River. The power plant has a 132 megawatt capacity and the spillway is capable of discharging 4,390 cubic meters per second of water. Construction was completed in 1928 (Manitoba Hydro 2004). The Great Falls spillway consists of four 80 m long vertical lift gates, each with its own dedicated hoist (Chouinard et al. 2003). The dam hierarchy is shown in Figure 5.2 and consists of seven levels. The highest level (level 1) reflects the overall spillway structure and is not shown. Higher levels are possible if one considers the entire dam and power plant structure from a perspective where the spillway is one element of that structure. An even higher level is possible if the entire system of dams along the Winnipeg River is analyzed, with the Great Falls dam considered to be one structure in the Pine Falls, Great Falls, McArthur Falls, Seven Sisters, Slave Falls, Pointe Du Bois system.

Level 2 represents the dam safety functions, which are the various failure modes. They include overtopping due to a design flood, overtopping due to a load rejection, an unintentional opening, failure to close, and drawdown of reservoir to prevent a dam failure. The analysis in this chapter examines overtopping due to a design flood, as shown in Figure 5.2. Chouinard et al. (2003) consider all five failure modes. The procedure is essentially the same for any failure mode, with only the importance factors changing. Since there is only one type of gate, level 3 is bypassed directly to level 4, which divides the spillway system into operational systems and equipment systems. The operational systems consist of the information needed to make a decision, the decision process itself, and the ability to get people to the equipment they need to operate. The equipment systems encompass the hoist/gate subsystem and the electrical subsystem that provides the power. These subsystems are divided into the lower-level subsystems in level 6. The hoist/gate subsystem consists of the spillway gates, their lifting mechanisms and the support structure. Because each gate has its own dedicated hoist, the hoist/gate subsystem is modeled as a parallel-series system, as shown in Figure 5.3.

Each of these subsystems is further broken down into components and subcomponents indicated by the letters *a* through *h* in Figure 5.2. Figure 5.4 through Figure 5.9 show the subsystems and components that the letters represent. Figure 5.4, for example, shows the subsystems and components for the gathering information subsystem. The information components include snow measuring stations, a flow prediction model, water level indicator system, gate position indicators, etc. Those blocks indicated by light blue are inspected directly and classified according to the categories listed on a component condition table. The condition table number e.g., C.2, C.4) from Chouinard et al. (2003) is listed in the figures. The component table for snow measuring stations, for example, is shown in Table 5.1. There are three condition states and they are subjective, not objective, in their description. The second condition state has a substantial range, from *CI=25* to *CI=69*. Some ranges (10 – 24 and 70 – 84) are not represented. This omission was considered acceptable because further definition and delineation was not effective for such a simple device with so few condition states. Generally, however, a better and more credible assessment of structural condition will be obtained if the component can be divided into as many clearly defined condition states as possible.

The components in yellow were not inspected directly. Their CI scores were obtained from subcomponent CI results and importance factors. Table 5.2 shows the component condition table for the reservoir level indicator system. It consists of three subcomponents: water level indicators, data acquisition device, and data transmission. These subcomponents are classified into six, four, and four condition states, respectively. These condition states relate to differing ranges of CI values, which will produce differing degrees of uncertainty in their results. Figure 5.5 follows the same convention for the components and subcomponents that comprise the decision process and the access and operations systems. Figure 5.6 covers the power supply, cables and controls, and support structure systems. Figure 5.7 is the gate system, and Figure 5.8 and Figure 5.9 look at the hoist system components and subcomponents.

Chouinard et al. (2003) used the lowest score of subcomponents and components to derive CI scores for subsystems and systems. For example, the CI score for reservoir level indicator system was *CI = 65* because that was the lowest score of the water level indicators (*CI = 85*), data acquisition device (*CI=65*), and data transmission (*CI=95*) subcomponents, as shown in Table 5.2. Importance factors were used at all levels in this study, which maintains a pure hierarchy and allows a component with multiple deficiencies to be distinguished from a component with only one deficiency. If a red flag is implemented whenever CI is less than 40 at the lowest inspectable level, there should be no danger of a deficiency going unnoticed. The importance factors are listed in Figure 5.2 through Figure 5.9. Those listed in purple circles are based on expert opinion and used in Chouinard et al. (2003). Those shown in light green were developed for this report and based on a assumption of equal importance among subcomponents unless there was a compelling reason to assume otherwise.

5.2 Inspection Results

The actual inspection results from the Great Falls spillway were used to apply the proposed methodology to that structure. Using the hierarchy shown in Figure 5.2 through Figure 5.9, the inspection results were combined with the importance factors shown in the figures to obtain the mean CI values, standard deviations, reliability indices, and probabilities of failure for the components and systems at each level. The starting point was the inspection results. It is assumed throughout that this is an initial inspection and that the mean value will be at the midpoint of the condition state. If these represented follow-on inspections, the mean value would shift as described in section 4.5 and Figure 4.1. The mean value and standard deviation for the reservoir level indicator system is obtained from the inspection results in Table 5.2 using equation 4.2.

Water Level Indicator: Range Classified by Inspector — 85 – 100

Mean Value: CI = 92.5

Standard Deviation: $$\sigma = \frac{100 - 92.5}{1.96} = 3.83 \tag{5.1}$$

Data Acquisition Device: Range Classified by Inspector — 40 – 84

Mean Value: CI = 62.0

Standard Deviation: $$\sigma = \frac{84.0 - 62.0}{1.96} = 11.22 \tag{5.2}$$

The computations for the data transmission subcomponent are the same as used for the water level indicator. In the actual inspection, the inspector was given considerable latitude in producing a CI score. The inspector chose to give the water level indicator a CI score of 85, the lowest in the category, but gave the data transmission a CI score of 95. The inspector gave the data acquisition device a CI score of 65, which is somewhere in the middle of a fairly large CS. There is no assurance that another inspector would see condition in exactly the same way. The approach proposed in this study instructs the inspector to choose only the correct condition state, which should provide much greater consistency between inspectors and thus, CI scores.

The mean CI and standard deviation for the reservoir level indicator (RLI) component, which is a series system consisting of the water level indicator, data acquisition, and data transmission subcomponents, are computed using equations 4.3 and 4.4 (see Chapter 4):

$$CI_{RLI-Component} = \sum_{j=1}^{n} I_j CI_j = (0.33)(92.5) + (0.33)(62.0) + (0.33)(92.5) = 82.3 \quad (5.3)$$

$$\sigma_{CI_{RLI-Component}} = \sqrt{\sum_{j=1}^{n} I_j^2 \sigma_j^2} = \sqrt{(0.33)^2(3.83)^2 + (0.33)^2(11.22)^2 + (0.33)^2(3.83)^2} = 4.15 \quad (5.4)$$

The reliability indices and probabilities of failure are computed using equations 2.4 and 2.5 (see Chapter 2):

$$\beta_{RLI-Component} = \frac{82.3 - 25}{\sqrt{(4.15)^2 + (12.5)^2}} = 4.27 \quad (5.5)$$

$$p_{f,RLI-Component} = \Phi(-4.27) = 9.61(10)^{-6} \quad (5.6)$$

Using the same approach for the other components and subcomponents, Table 5.3 shows the results for the gathering information, decision process, and access and operations systems. The components and subcomponents are numbered to reflect the hierarchy shown in Figure 4.2 through Figure 4.9. The importance factors, mean CI value, standard deviation, and reliability index are listed. The rows in light blue were inspected directly from the component table listed and the rows in yellow reflect higher-order indices derived from a combination of inspection results and importance factors. Table 5.4 shows the same information for the components and subcomponents of the power supply, cables and controls, and supporting structure subsystems. Table 5.5 and Table 5.6 reflect the gate and hoist subsystems, respectively.

Table 5.7 combines the results from Table 5.3 through Table 5.6 to provide the CI and reliability results for the subsystems, systems, and overall structure. The mean CI of the overall structure is $CI=84.02$. The structure is in excellent condition and the reliability index of $\beta=4.61$ reflects little likelihood that it needs to be replaced or rehabilitated. The least-functional system of the structure was the decision making process. It was part of the operational system, which was given a smaller importance factor ($I=0.3$) than the equipment system ($I=0.7$) and thus had less effect on the overall structure rating.

Assuming independence of the components caused the standard deviation of the CIs to get progressively smaller as the calculations progressed up the hierarchy. This is not a conservative assumption because the smaller standard deviations will produce smaller reported probabilities of failure. The ice and debris management and gate position indicator components in Table 5.3 provide an illustrative example. The mean and standard deviation for each of the subcomponents were all N[92.5, 3.38], with an in importance factor of 0.33 assigned to each subcomponent. The resulting component CI was N[92.5, 2.21] using equations 3.1 and 4.4. When the importance factors are less than 1.0 (as they always are), the standard deviation will decrease when using equations that are based on independent failure modes. Table 5.7 illustrates that at the highest level for this structure, the standard deviation has been reduced to 0.90. An assumption of perfect correlation would have produced higher standard deviations at the system levels. Either assuming perfect correlation or estimating the actual correlation would have complicated the computations and would not necessarily have been any more valid. However, the issue merits further study.

Table 5.3 through Table 5.7 illustrate that the methodology applied to a simple hypothetical structure in Chapter 4 is equally applicable to a large, complex structure, and the level of difficulty is not much higher than that for a deterministic analysis. The condition of the structure at successively higher levels reflects both the inspection results and the relative importance of the various components. The best results will be obtained when the component condition tables are delineated into as many clearly defined condition states as practicable.

5.3 System Probability Approaches

Returning to the discussion in section 4.10 , the CI system proposed in this report is compared with the traditional reliability approach. Table 5.8 compares the two approaches for the gathering information, decision process, and access and operations systems. Using the reservoir level indicator from Table 5.2 as an example, the results from Table 5.3 indicate the following for the subcomponents:

Water Level Indicator	β=5.07	$p_f=\Phi(-\beta)=\Phi(-5.07)=2.00(10^{-7})$	
Data Acquisition Device	β=2.18	$p_f=\Phi(-\beta)=\Phi(-2.18)=0.0147$	(5.7)
Data Transmission	β=5.07	$p_f=\Phi(-\beta)=\Phi(-5.07)=2.00(10^{-7})$	

Equation 5.6 computed the probability of failure using the current proposal. Assuming the components are independent, equation 2.10 (see Chapter 2) is used to compute the probability of failure for the reservoir level component (RLI), which is a series system of the listed subcomponents:

$$p_{f,RLI-Component} = 1-((1-2.00*10^{-7})(1-0.0147)(1-2.00*10^{-7})) = 0.0147 \quad (5.8)$$

Assuming the components are perfectly correlated, the component probability is:

$$p_{f,RLI-Component} = p_{f,\max-Sub-component} = 0.0147 \quad (5.9)$$

In this case, the independent and perfectly correlated results were identical because the probability of failure of the Data Acquisition Device was so much higher than that for the other two subcomponents. The same process is used for the other components in Table 5.8. There was a larger discrepancy between the independent and perfectly correlated results for the gathering information system of which the reservoir level indicator was a part — 0.287 for independent versus 0.098 for perfectly correlated. Table 5.9 through Table 5.11 show the same calculations for additional components, the gate, and the hoist, respectively.

Table 5.12 shows the results for the higher-level subsystems, systems, and the entire structure. Using the weighted average approach, the probability of failure, which reflects the probability of the structure needing replacement or rehabilitation, is $p_{f,Structure} = 1.96*10^{-6}$. This result represents a low likelihood of replacement, which makes sense given the excellent condition of the structure and its most important systems and components. The issue of whether that number is in fact accurate merits further study. Using the traditional reliability approach, if the components are independent, the probability of failure is 0.445, and if they are perfectly correlated, the failure probability is 0.098. Given all the components and systems on the structure, there is somewhere between a 10% and 45% chance that something will fail somewhere on the structure. It will most likely occur in the operations rather than the equipment portion of the structure, and some estimation of correlation becomes important.

One could argue that a traditional reliability approach cannot adequately analyze the gathering information and decision process systems, which do not truly represent series systems. The spillway gate could still be operated even if the snow measuring devices or the public protection warning system fail. As noted previously, the system CI methodology proposed here represents a significant departure from traditional system reliability methods. An advantage the proposed approach is that the analyst can incorporate anything that he or she thinks is relevant to the structure into the analysis. Because the goal is to attain an overall score for the structure to allow comparison with other structures, any variable can be included, even if it is difficult to define.

One variable of current interest not yet discussed in the context of the proposed risk estimation methodology is a structure's vulnerability sabotage or terrorism. That topic is addressed in the next chapter.

Table 5.1. Component condition table and actual inspection results for snow measuring stations, part of the gathering information system on the Great Falls spillway.

Snow Measuring Stations (Chouinard *et.al.* 2003 Table C.4)									
Function									
Excellent	Measurement of snow cover depth at an adequate number of locations with sufficient frequency for dam safety purposes.								
Failed	Not measuring snow depth cover in the watershed where applicable.								
	0 -- 9	10 -- 24	25 -- 39	40 -- 54	55 -- 69	70 -- 84	85 -- 100	Score	Comments
Indicator	1	2	3	4	5	6	7	S	
Measurement of snow cover depth at an adequate number of locations with sufficient frequency for dam safety purposes							X		Winter precipitation tracked but not evaporation etc; remote sensing used to obtain snow water contents; limited Env't Canada measurement sites; info used qualitatively only - not in models.
Inadequate number of snow measurement locations and/or insufficient frequency of readings			X	X	X			50	
Not measuring snow depth cover in the watershed where applicable	X								

Table 5.2. Component condition table and actual inspection results for reservoir-level indicator, part of the gathering information system on the Great Falls spillway.

Water Level Indicator System for Reservoir level (Chouinard et.al. 2003 Table C.2)

Function									
Excellent	Providing accurate data, redundancy and no evidence of malfunction (water level in the reservoir) for dam safety purposes. Instrument regularly checked and calibrated.								
Failed	Not providing accurate data, not functioning.								
	0 -- 9	10 -- 24	25 -- 39	40 -- 54	55 -- 69	70 -- 84	85 -- 100	Score	Comments
Indicator	1	2	3	4	5	6	7	S	
Water level indicators									
Measuring level accurately and continuously and adequate number for dam safety purposes							X	85	Forebay water level gauge in powerhouse.
Inadequate water level indicators to determine the influence of wind on pool level				X	X	X			
Poorly located (influenced by gate opening or difficult to read)			X	X	X				
Inadequate frequency of measurement			X	X					
No redundancy (only one gauge near the dam or spillway)		X	X	X					
Not providing accurate data, not functioning	X								
Data acquisition device									
Recording data continuously accurately and reliably.							X		Aging equipment; accuracy dependent on gauge maintenance; historically somewhat troublesome.
Recording data intermittently but still adequate				X	X	X		65	
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								
Data transmission									
Transmitting data continuously accurately and reliably.							X	95	Data delivered via SCADA network; new communications equipment has improved reliability, problems now rare.
Transmittinging data intermittently but still adequate				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								

Table 5.3. CI and reliability results for the gathering information, decision process, and access and operations systems on the Great Falls spillway.

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Gathering Information	7a		76.72	2.01	4.01	
River Flow Measurement	7a.1	0.11	82.33	4.15	4.27	C.1
Water Level Indicator	7a.1.1	0.33	92.50	3.83	5.07	
Data Acquisition Device	7a.1.2	0.33	92.50	3.83	5.07	
Data Transmission	7a.1.3	0.33	62.00	11.22	2.18	
Reservoir Level Indicator	7a.2	0.11	82.33	4.15	4.27	C.2
Water Level Indicator	7a.2.1	0.33	92.50	3.83	5.07	
Data Acquisition Device	7a.2.2	0.33	62.00	11.22	2.18	
Data Transmission	7a.2.3	0.33	92.50	3.83	5.07	
Precipitation & Temp. Gauge	7a.3	0.11	77.33	4.15	3.90	C.3
Precip & Temp Gauges	7a.3.1	0.33	47.00	11.22	1.29	
Data Acquisition Device	7a.3.2	0.33	92.50	3.83	5.07	
Data Transmission	7a.3.3	0.33	92.50	3.83	5.07	
Snow Measuring Model	7a.4	0.11	47.00	11.22	1.29	C.4
Flow Predicition Model	7a.5	0.11	47.00	11.22	1.29	C.9
Weather Forecasting	7a.6	0.11	77.00	3.57	3.93	C.5
Ice and Debris Management	7a.7	0.11	92.50	2.21	5.21	C.6
Monitoring	7a.7.1	0.33	92.50	3.83	5.07	
Management	7a.7.2	0.33	92.50	3.83	5.07	
Control Equipment	7a.7.3	0.33	92.50	3.83	5.07	
Gate Position Indicator	7a.8	0.11	92.50	2.21	5.21	C.8
Position Indicator	7a.8.1	0.33	92.50	3.83	5.07	
Data Acquisition Device	7a.8.2	0.33	92.50	3.83	5.07	
Data Transmission	7a.8.3	0.33	92.50	3.83	5.07	
Third-Party Flow Data	7a.9	0.11	92.50	3.83	5.07	C.7
Decision Process	7b		62.10	4.27	2.76	
Data Processing	7b.1	0.20	92.50	3.83	5.07	Ssheet
Analysis	7b.2	0.20	47.00	11.22	1.29	Ssheet
Decision Process	7b.3	0.20	47.00	11.22	1.29	C.10
Public Protection Warning System	7b.4	0.20	62.00	11.22	2.18	C.12
Operation Procedures	7b.5	0.20	62.00	7.94	2.46	C.15
Standard Operating Procedures	7b.5.1	0.50	62.00	11.22	2.18	
Autonomous Operating Proc.	7b.5.2	0.50	62.00	11.22	2.18	
Access and Operations	7c		92.50	1.43	5.26	
Avail. and Mobilization (Load Rejectio	7c.1	0.20	92.50	2.71	5.18	C.14
Availablity	7c.1.1	0.50	92.50	3.83	5.07	
Mobilization	7c.1.2	0.50	92.50	3.83	5.07	
Avail. and Mobilization (Load Rejectio	7c.2	0.20	92.50	2.71	5.18	C.13
Availablity	7c.2.1	0.50	92.50	3.83	5.07	
Mobilization	7c.2.2	0.50	92.50	3.83	5.07	
Qualification / Training of Operator	7c.3	0.20	92.50	3.83	5.07	C.18
Local Access	7c.4	0.20	92.50	2.71	5.18	C.22
Pedestrian Access	7c.4.1	0.50	92.50	3.83	5.07	
Keys and Locks	7c.4.2	0.50	92.50	3.83	5.07	
Lighting System	7c.5	0.20	92.50	3.83	5.07	C.29

Table 5.4. CI and reliability results for the power supply, cables and controls, and supporting structure subsystems on the Great Falls spillway.

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Power Supply			86.25	2.07	4.74	
Local or Emergency Generators	7d	1.00	86.25	2.07	4.74	C.25
Frequency and Voltage	7d.1	0.08	85.00	7.65	4.03	
Engine Temperature / Oil Pressure	7d.2	0.08	85.00	7.65	4.03	
Starting Sequence	7d.3	0.08	85.00	7.65	4.03	
Noise and Vibratiion	7d.4	0.08	85.00	7.65	4.03	
Functional Test	7d.5	0.08	92.50	3.83	5.07	
Fuel	7d.6	0.08	92.50	3.83	5.07	
Batteries	7d.7	0.08	85.00	7.65	4.03	
Battery Charger	7d.8	0.08	85.00	7.65	4.03	
Alternator	7d.9	0.08	85.00	7.65	4.03	
Lubrication	7d.10	0.08	85.00	7.65	4.03	
Cooling System	7d.11	0.08	85.00	7.65	4.03	
Intake and Exhaust System	7d.12	0.08	85.00	7.65	4.03	
Cables and Controls	7e		87.94	2.57	4.84	
Underground and Encased Cables	7e.1	0.25	85.00	5.41	4.33	C.24
Insulation	7e.1.1	0.50	85.00	7.65	4.03	
Terminators	7e.1.2	0.50	85.00	7.65	4.03	
Power Feeder Cables	7e.2	0.25	85.00	5.41	4.33	C.25
Insulation	7e.2.1	0.50	85.00	7.65	4.03	
Terminators	7e.2.2	0.50	85.00	7.65	4.03	
Transformer	7e.3	0.25	89.25	5.69	4.60	C.26
Dielectric	7e.3.1	0.00	N/A	N/A	N/A	
Insulation	7e.3.2	0.50	85.00	7.65	4.03	
Windings	7e.3.3	0.55	85.00	7.65	4.03	
Tank	7e.3.4	0.00	N/A	N/A	N/A	
Power Source Transfer System	7e.4	0.25	92.50	3.83	5.07	C.27
Test (Transfer Switch)	7e.4.1	0.00	N/A	N/A	N/A	
Test (Manual Transfer Device)	7e.4.2	1.00	92.50	3.83	5.07	
Supporting Structure	6e		92.50	2.07	5.22	
Lifting Device Structure (Steel)	7f.1	0.50	92.50	1.56	5.25	C.64
Displacement / Deterioration	7f.1.1	0.17	92.50	3.83	5.07	
Anchor Bolts	7f.1.2	0.17	92.50	3.83	5.07	
Cracks	7f.1.3	0.17	92.50	3.83	5.07	
Distortion	7f.1.4	0.17	92.50	3.83	5.07	
Corrosion	7f.1.5	0.17	92.50	3.83	5.07	
Missing or Loose Parts	7f.1.6	0.17	92.50	3.83	5.07	
Lifting Device Structure (Concrete)	7f.2	0.50	92.50	3.83	5.07	C.61

(Yellow) Derived from a Combination of Inspected Items

(Cyan) Directly Measured by Inspection

Table 5.5. CI and reliability results for the gate subsystem on the Great Falls spillway.

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Gate #1	7g		90.48	1.25	5.11	
Gate Structure and Support	7g.1	0.90	90.26	1.17	5.09	
Approach and Exit Channel	7g.1.1	0.17	92.50	1.71	5.25	C.63
Loss of Concrete Apron	7g.1.1.1	0.20	92.50	3.83	5.07	
Loss of Concrete Pier/Base	7g.1.1.2	0.20	92.50	3.83	5.07	
Scour of Foundation	7g.1.1.3	0.20	92.50	3.83	5.07	
Upstream Sedimentation	7g.1.1.4	0.20	92.50	3.83	5.07	
Downstream Blockage	7g.1.1.5	0.20	92.50	3.83	5.07	
Embedded Parts	7g.1.2	0.17	80.30	3.28	4.20	C.65
Gate Lifting Effort	7g.1.2.1	0.20	92.50	3.83	5.07	
Geometrical Alignment Roller	7g.1.2.2	0.20	62.00	11.22	2.18	
Roller Path Corrosion	7g.1.2.3	0.20	69.50	7.40	3.02	
Roller Tooth Wear	7g.1.2.4	0.20	92.50	3.83	5.07	
Corrosion Remainder	7g.1.2.5	0.20	85.00	7.65	4.03	
Gate Structure	7g.1.3	0.17	91.25	1.91	5.14	C.66
Loading History	7g.1.3.1	0.17	92.50	3.83	5.07	
Cracks	7g.1.3.2	0.17	92.50	3.83	5.07	
Distortion	7g.1.3.3	0.17	92.50	3.83	5.07	
Skin Plate Corrosion	7g.1.3.4	0.17	85.00	7.65	4.03	
Tension/Comp. Corrosion	7g.1.3.5	0.17	92.50	3.83	5.07	
Missing or Loose Parts	7g.1.3.6	0.17	92.50	3.83	5.07	
Closure Structure (Stop Log, Bulk	7g.1.4	0.17	92.50	1.56	5.25	C.67
Structural Evaluation	7g.1.4.1	0.17	92.50	3.83	5.07	
Cracks	7g.1.4.2	0.17	92.50	3.83	5.07	
Distortion	7g.1.4.3	0.17	92.50	3.83	5.07	
Skin Plate Corrosion	7g.1.4.4	0.17	92.50	3.83	5.07	
Tension/Comp. Corrosion	7g.1.4.5	0.17	92.50	3.83	5.07	
Missing or Loose Parts	7g.1.4.6	0.17	92.50	3.83	5.07	
Bottom and Side Seals	7g.1.5	0.17	92.50	3.83	5.07	C.68
Ice Prevention	7g.1.6	0.17	92.50	3.83	5.07	C.31
Access and Control	7g.2	0.10	92.50	3.83	5.07	
Remote and Onsite Controls	7g.2.1	1.00	92.50	3.83	5.07	C.23

Legend:
- (Yellow) Derived from a Combination of Inspected Items
- (Cyan) Directly Measured by Inspection

Table 5.6. CI and reliability results for the hoist subsystem on the Great Falls spillway.

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Reference Table
Level 7: Components						
Hoist #1	6c.1		91.85	0.95	5.23	
Power Supply and Controls	7h.1	0.50	92.50	1.61	5.25	
Limit Switches	7h.1.1	0.25	92.50	3.83	5.07	C.30
Motor Control Center	7h.1.2	0.25	92.50	2.21	5.21	C.35
Functional Test	7h.1.2.1	0.33	92.50	3.83	5.07	
Visual Inspection	7h.1.2.2	0.33	92.50	3.83	5.07	
Cabinet Heating	7h.1.2.3	0.33	92.50	3.83	5.07	
Distribution Panel	7h.1.3	0.25	92.50	2.71	5.18	C.32
Functional Test	7h.1.3.1	0.50	92.50	3.83	5.07	
Visual Inspection	7h.1.3.2	0.50	92.50	3.83	5.07	
Cabinet Heating	7h.1.3.3	0.00	N/A	N/A	N/A	
Cam Switches	7h.1.4	0.25	92.50	3.83	5.07	C.36
Functional Test	7h.1.4.1	1.00	92.50	3.83	5.07	
Overheating or Arching	7h.1.4.2	0.00	N/A	N/A	N/A	
Force Transmission	7h.2	0.50	91.20	1.00	5.17	
Split Bush./Journal Bearing	7h.2.1	0.09	92.50	3.83	5.07	C.41
Rotating Shaft	7h.2.2	0.09	90.63	2.53	5.05	C.42
Corrosion	7h.2.2.1	0.25	92.50	3.83	5.07	
Warping or Misalign	7h.2.2.2	0.25	92.50	3.83	5.07	
Cracking	7h.2.2.3	0.25	85.00	7.65	4.03	
Missing bolts or comp	7h.2.2.4	0.25	92.50	3.83	5.07	
Gear Assembly	7h.2.3	0.09	89.50	2.54	4.96	C.43
Noise, vibration, jump	7h.2.3.1	0.20	85.00	7.65	4.03	
Toothwear, contact	7h.2.3.2	0.20	92.50	3.83	5.07	
Anchor	7h.2.3.3	0.20	92.50	3.83	5.07	
Bearing / Bushing Wear	7h.2.3.4	0.20	85.00	7.65	4.03	
Lubricant	7h.2.3.5	0.20	92.50	3.83	5.07	
Wheel, axle and bearings	7h.2.4	0.09	92.50	3.83	5.07	C.58
Lifting Connectors (non-ded)	7h.2.5	0.09	92.50	3.83	5.07	C.46
Lifting Connectors (ded)	7h.2.6	0.09	92.50	3.83	5.07	C.45
Drum Sheaves and Pulleys	7h.2.7	0.09	90.63	2.53	5.05	C.49
Variable of Measureable Wear	7h.2.7.1	0.25	92.50	3.83	5.07	
Corrosion	7h.2.7.2	0.25	85.00	7.65	4.03	
Groove Wear	7h.2.7.3	0.25	92.50	3.83	5.07	
Wire rope Clamps/Anchors	7h.2.7.4	0.25	92.50	3.83	5.07	
Brake (hoist)	7h.2.8	0.09	92.50	3.83	5.07	C.50
Fan Brake	7h.2.9	0.09	92.50	3.83	5.07	C.52
Wire Rope & Connectors	7h.2.10	0.09	92.50	1.91	5.23	C.53
Kinking	7h.2.10.1	0.25	92.50	3.83	5.07	
Corrosion	7h.2.10.2	0.25	92.50	3.83	5.07	
Outer Wire Wear/Breakage	7h.2.10.3	0.25	92.50	3.83	5.07	
Tension	7h.2.10.4	0.25	92.50	3.83	5.07	
Lifting Motor (electric)	7h.2.11	0.09	85.00	3.12	4.57	C.34
Insulators	7h.2.11.1	0.17	85.00	7.65	4.03	
Apparent Temperature	7h.2.11.2	0.17	85.00	7.65	4.03	
Overloading	7h.2.11.3	0.17	85.00	7.65	4.03	
Impaired Ventilation	7h.2.11.4	0.17	85.00	7.65	4.03	
Bearings and Bushings	7h.2.11.5	0.17	85.00	7.65	4.03	
Noise and Vibrations	7h.2.11.6	0.17	85.00	7.65	4.03	

Table 5.7. CI and reliability results for the higher-level subsystems, systems, and spillway structure on the Great Falls spillway.

Item	Number	Importance	Mean CI	Standard Deviation	Reliability Index	Supporting Items
Level 2: Dam Safety Functions						
Overtopping Design Flood	2a		84.02	0.90	4.61576	4a, 4b
Level 3: Type of Gate						
Level 4: Operational Sys. and Equip.						
Operations	4a	0.3	70.26	2.45	3.48447	5a, 5b, 5c
Equipment	4b	0.7	89.92	0.73	5.08116	5d, 5e
Level 5: Systems						
Gathering Information	5a	0.35	76.72	2.01	4.00574	sep. sheet
Decision Process	5b	0.55	62.10	4.27	2.75826	sep. sheet
Access and Operation	5c	0.1	92.50	1.43	5.25897	sep. sheet
Electrical	5d	0.4	87.26	1.75	4.83613	6a, 6b
Hoist / Gate System	5e	0.6	91.69	0.37	5.22615	6c, 6d, 6e
Level 6: Sub-Systems						
Power Supply	6a	0.40	86.25	2.07	4.74019	sep. sheet
Cables and Controls	6b	0.6	87.94	2.57	4.83719	sep. sheet
Gate-Hoist Sub-System	6cd	0.95	91.65	0.38	5.22275	6cd.1-4
Hoist 1 / Gate 1	6cd.1	0.25	91.58	0.80	5.20956	6c.1, 6d.1
Hoist 2 / Gate 2	6cd.2	0.25	91.67	0.73	5.21812	6c.2, 6d.2
Hoist 3 / Gate 3	6cd.3	0.25	91.67	0.73	5.22	6c.3, 6d.3
Hoist 4 / Gate 4	6cd.4	0.25	91.67	0.73	5.22	6c.4, 6d.4
Hoist 1	6c.1	0.80	91.85	0.95	5.23	sep. sheet
Hoist 2	6c.2	0.80	92.19	0.85	5.26	sep. sheet
Hoist 3	6c.3	0.80	92.19	0.85	5.26	sep. sheet
Hoist 4	6c.4	0.80	92.19	0.85	5.26	sep. sheet
Gate 1	6d.1	0.20	90.48	1.25	5.11	sep. sheet
Gate 2	6d.2	0.20	89.57	1.35	5.03	sep. sheet
Gate 3	6d.3	0.20	89.57	1.35	5.03	sep. sheet
Gate 4	6d.4	0.20	89.57	1.35	5.03	sep. sheet
Supporting Structure	6e	0.05	92.50	2.07	5.22	sep. sheet

(yellow) Derived from a Combination of Inspected Items

(cyan) Directly Measured by Inspection

Table 5.8. Comparison of probabilistic CI system with traditional system reliability approach for both independent and perfectly correlated components on the gathering information, decision process, and access and operations systems of the Great Falls spillway.

Item	Component pf	System pf Weighted Average	System pf Statistical Independence	System pf Perfect Correlation
Level 7: Components				
Gathering Information		3.09264E-05	0.28686493	0.097689389
River Flow Measurement		9.60546E-06	0.014715658	0.014715263
Water Level Indicator	2.00486E-07			
Data Acquisition Device	2.00486E-07			
Data Transmission	0.014715263			
Reservoir Level Indicator		9.60546E-06	0.014715658	0.014715263
Water Level Indicator	2.00486E-07			
Data Acquisition Device	0.014715263			
Data Transmission	2.00486E-07			
Precipitation & Temp. Gauge		4.78599E-05	0.097689751	0.097689389
Precip & Temp Gauges	0.097689389			
Data Acquisition Device	2.00486E-07			
Data Transmission	2.00486E-07			
Snow Measuring Model	0.097689389			
Flow Predicition Model	0.097689389			
Weather Forecasting	4.32368E-05			
Ice and Debris Management		9.24035E-08	6.01459E-07	2.00486E-07
Monitoring	2.00486E-07			
Management	2.00486E-07			
Control Equipment	2.00486E-07			
Gate Position Indicator		9.24035E-08	6.01459E-07	2.00486E-07
Position Indicator	2.00486E-07			
Data Acquisition Device	2.00486E-07			
Data Transmission	2.00486E-07			
Third-Party Flow Data	2.00486E-07			
Decision Process		0.002905596	0.221251349	0.097689389
Data Processing	2.00486E-07			
Analysis	0.097689389			
Decision Process	0.097689389			
Public Protection Warning System	0.014715263			
Operation Procedures		0.006890764	0.029213987	0.014715263
Standard Operating Procedures	0.014715263			
Autonomous Operating Proc.	0.014715263			
Access and Operations		7.25771E-08	1.60389E-06	2.00486E-07
Avail. and Mobilization (Load Rejection)		1.13071E-07	4.00973E-07	2.00486E-07
Availablity	2.00486E-07			
Mobilization	2.00486E-07			
Avail. and Mobilization (Load Rejection)		1.13071E-07	4.00973E-07	2.00486E-07
Availablity	2.00486E-07			
Mobilization	2.00486E-07			
Qualification / Training of Operator	2.00486E-07			
Local Access		1.13071E-07	4.00973E-07	2.00486E-07
Pedestrian Access	2.00486E-07			
Keys and Locks	2.00486E-07			
Lighting System	2.00486E-07			

Table 5.9. Comparison of probabilistic CI system with traditional system reliability approach for both independent and perfectly correlated components on the power supply, cables and controls, and supporting structure subsystems on the Great Falls spillway.

Item	Component pf	System pf Weighted Average	System pf Statistical Independence	System pf Perfect Correlation
Level 7: Components				
Power Supply		1.06889E-06	0.000275091	2.74724E-05
Local or Emergency Generators		1.06889E-06	0.000275091	2.74724E-05
Frequency and Voltage	2.74724E-05			
Engine Temperature / Oil Pressure	2.74724E-05			
Starting Sequence	2.74724E-05			
Noise and Vibratiion	2.74724E-05			
Functional Test	2.00486E-07			
Fuel	2.00486E-07			
Batteries	2.74724E-05			
Battery Charger	2.74724E-05			
Alternator	2.74724E-05			
Lubrication	2.74724E-05			
Cooling System	2.74724E-05			
Intake and Exhaust System	2.74724E-05			
Cables and Controls		6.59336E-07	0.000165024	2.74724E-05
Underground and Encased Cables		7.44806E-06	5.49441E-05	2.74724E-05
Insulation	2.74724E-05			
Terminators	2.74724E-05			
Power Feeder Cables		7.44806E-06	5.49441E-05	2.74724E-05
Insulation	2.74724E-05			
Terminators	2.74724E-05			
Transformer		2.11036E-06	5.49441E-05	2.74724E-05
Dielectric	N/A			
Insulation	2.74724E-05			
Windings	2.74724E-05			
Tank	N/A			
Power Source Transfer System		2.00486E-07	2.00486E-07	2.00486E-07
Test (Transfer Switch)	N/A			
Test (Manual Transfer Device)	2.00486E-07			
Supporting Structure		8.77766E-08	1.60389E-06	2.00486E-07
Lifting Device Structure (Steel)		7.50719E-08	1.4034E-06	2.00486E-07
Displacement / Deterioration	2.00486E-07			
Anchor Bolts	2.00486E-07			
Cracks	2.00486E-07			
Distortion	2.00486E-07			
Corrosion	2.00486E-07			
Missing or Loose Parts	2.00486E-07			
Lifting Device Structure (Concrete)	2.00486E-07			

Table 5.10. Comparison of probabilistic CI system with traditional system reliability approach for both independent and perfectly correlated components on the gate subsystems on the Great Falls spillway.

Item	Component pf	System pf Weighted Average	System pf Statistical Independence	System pf Perfect Correlation
Level 7: Components				
Gate #1		1.61924E-07	0.016027391	0.014715263
Gate Structure and Support		1.74709E-07	0.016027194	0.014715263
Approach and Exit Channel		7.82941E-08	1.00243E-06	2.00486E-07
Loss of Concrete Apron	2.00486E-07			
Loss of Concrete Pier/Base	2.00486E-07			
Scour of Foundation	2.00486E-07			
Upstream Sedimentation	2.00486E-07			
Downstream Blockage	2.00486E-07			
Embedded Parts		1.34074E-05	0.01599661	0.014715263
Gate Lifting Effort	2.00486E-07			
Geometrical Alignment Roller	0.014715263			
Roller Path Corrosion	0.001272646			
Roller Tooth Wear	2.00486E-07			
Corrosion Remainder	2.74724E-05			
Gate Structure		1.40177E-07	2.84748E-05	2.74724E-05
Loading History	2.00486E-07			
Cracks	2.00486E-07			
Distortion	2.00486E-07			
Skin Plate Corrosion	2.74724E-05			
Tension/Comp. Corrosion	2.00486E-07			
Missing or Loose Parts	2.00486E-07			
Closure Structure (Stop Log, Bulkheads)		7.50719E-08	1.20292E-06	2.00486E-07
Structural Evaluation	2.00486E-07			
Cracks	2.00486E-07			
Distortion	2.00486E-07			
Skin Plate Corrosion	2.00486E-07			
Tension/Comp. Corrosion	2.00486E-07			
Missing or Loose Parts	2.00486E-07			
Bottom and Side Seals	2.00486E-07			
Ice Prevention	2.00486E-07			
Access and Control		2.00486E-07	2.00486E-07	2.00486E-07
Remote and Onsite Controls	2.00486E-07			

Table 5.11. Comparison of probabilistic CI system with the traditional system reliability approach for both independent and perfectly correlated components on the hoist subsystems on the Great Falls spillway.

Item	Component pf	System pf Weighted Average	System pf Statistical Independence	System pf Perfect Correlation
Level 7: Components				
Hoist #1		8.63914E-08	0.0005002	2.74724E-05
Power Supply and Controls		7.60663E-08	1.4034E-06	2.00486E-07
Limit Switches	2.00486E-07			
Motor Control Center		9.24035E-08	6.01459E-07	2.00486E-07
Functional Test	2.00486E-07			
Visual Inspection	2.00486E-07			
Cabinet Heating	2.00486E-07			
Distribution Panel		1.13071E-07	4.00973E-07	2.00486E-07
Functional Test	2.00486E-07			
Visual Inspection	2.00486E-07			
Cabinet Heating	N/A			
Cam Switches		2.00486E-07	2.00486E-07	2.00486E-07
Functional Test	2.00486E-07			
Overheating or Arching	N/A			
Force Transmission		1.14401E-07	0.000498797	2.74724E-05
Split Bush./Journal Bearing	2.00486E-07			
Rotating Shaft		2.25238E-07	8.36179E-05	2.74724E-05
Corrosion	2.00486E-07			
Warping or Misalign	2.00486E-07			
Cracking	2.74724E-05			
Missing bolts or comp	2.00486E-07			
Gear Assembly		3.53813E-07	5.55455E-05	2.74724E-05
Noise, vibration, jump	2.74724E-05			
Toothwear, contact	2.00486E-07			
Anchor	2.00486E-07			
Bearing / Bushing Wear	2.74724E-05			
Lubricant	2.00486E-07			
Wheel, axle and bearings	2.00486E-07			
Lifting Connectors (non-ded)	2.00486E-07			
Lifting Connectors (ded)	2.00486E-07			
Drum Sheaves and Pulleys		2.25238E-07	2.80739E-05	2.74724E-05
Variable of Measureable Wear	2.00486E-07			
Corrosion	2.74724E-05			
Groove Wear	2.00486E-07			
Wire rope Clamps/Anchors	2.00486E-07			
Brake (hoist)	2.00486E-07			
Fan Brake	2.00486E-07			
Wire Rope & Connectors		8.33506E-08	0.000165625	2.00486E-07
Kinking	2.00486E-07			
Corrosion	2.00486E-07			
Outer Wire Wear/Breakage	2.00486E-07			
Tension	2.00486E-07			
Lifting Motor (electric)		2.45357E-06	0.000164823	2.74724E-05
Insulators	2.74724E-05			
Apparent Temperature	2.74724E-05			
Overloading	2.74724E-05			
Impaired Ventilation	2.74724E-05			
Bearings and Bushings	2.74724E-05			
Noise and Vibrations	2.74724E-05			

Table 5.12. Comparison of probabilistic CI system with the traditional system reliability approach for both independent and perfectly correlated components on the higher-level subsystems, systems and spillway structure on the Great Falls spillway.

Item	System pf Weighted Average	System pf Statistical Independence	System pf Perfect Correlation
Level 2: Dam Safety Functions			
Overtopping Design Flood	1.96034E-06	0.444893242	0.097689389
Level 3: Type of Gate			
Level 4: Operational Sys. and Equip.			
Operations	0.000246599	0.444647917	0.097689389
Equipment	1.87888E-07	0.000441747	0.014715263
Level 5: Systems			
Gathering Information	3.09264E-05	0.28686493	0.097689389
Decision Process	0.002905596	0.221251349	0.097689389
Access and Operation	7.25771E-08	1.60389E-06	2.00486E-07
Electrical	6.6284E-07	0.00044007	2.74724E-05
Hoist / Gate System	8.67067E-08	1.67836E-06	0.014715263
Level 6: Sub-Systems			
Power Supply	1.06889E-06	0.000275091	2.74724E-05
Cables and Controls	6.59336E-07	0.000165024	2.74724E-05
Gate-Hoist Sub-System	8.83125E-08	7.44724E-08	0.014715263
Hoist 1 / Gate 1	9.48291E-08	0.016519574	0.014715263
Hoist 2 / Gate 2	9.05476E-08	0.016519574	0.014715263
Hoist 3 / Gate 3	9.05476E-08	0.016519574	0.014715263
Hoist 4 / Gate 4	9.05476E-08	0.016519574	0.014715263
Hoist 1	8.63914E-08	0.0005002	2.74724E-05
Hoist 2	7.36896E-08	0.0005002	2.74724E-05
Hoist 3	7.36896E-08	0.0005002	2.74724E-05
Hoist 4	7.36896E-08	0.0005002	2.74724E-05
Gate 1	1.61924E-07	0.016027391	0.014715263
Gate 2	2.40621E-07	0.016027391	0.014715263
Gate 3	2.40621E-07	0.016027391	0.014715263
Gate 4	2.40621E-07	0.016027391	0.014715263
Supporting Structure	8.77766E-08	1.60389E-06	2.00486E-07

Figure 5.1. Great Falls dam on the Winnipeg River (Manitoba Hydro 2004).

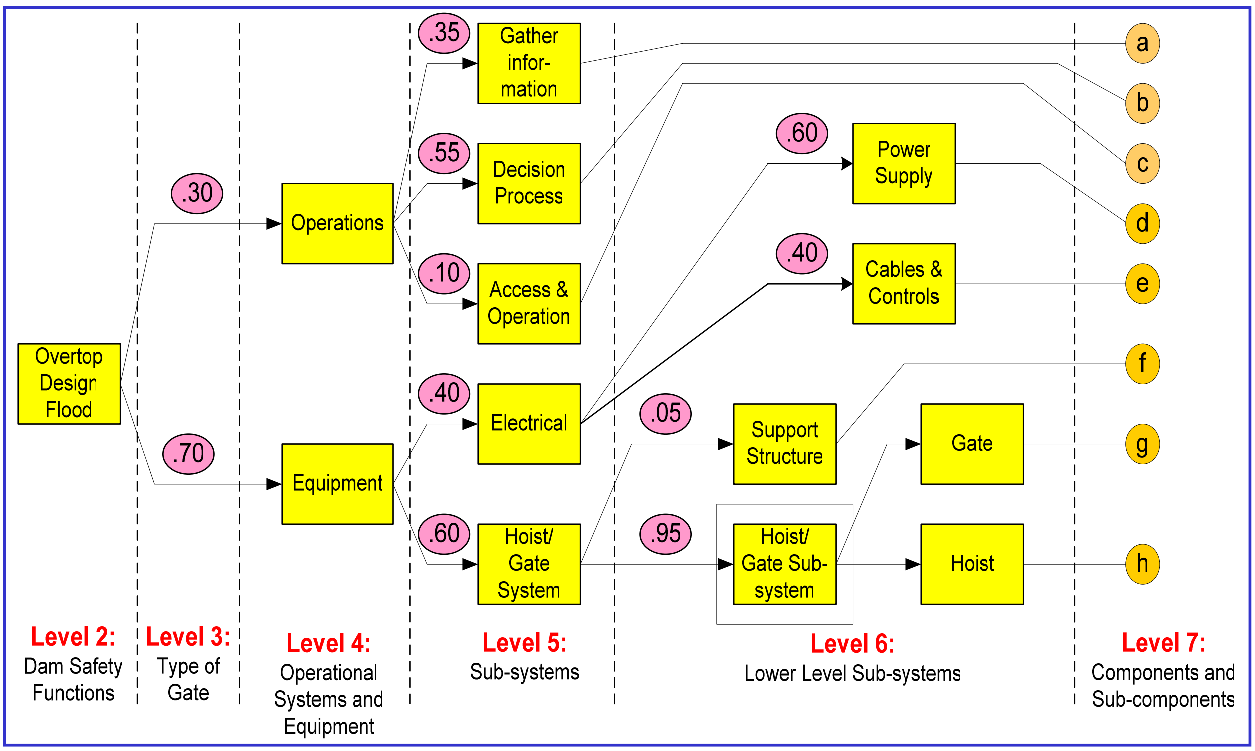


Figure 5.2. The seven-level hierarchy of systems, subsystems, and components that comprise the Great Falls spillway.

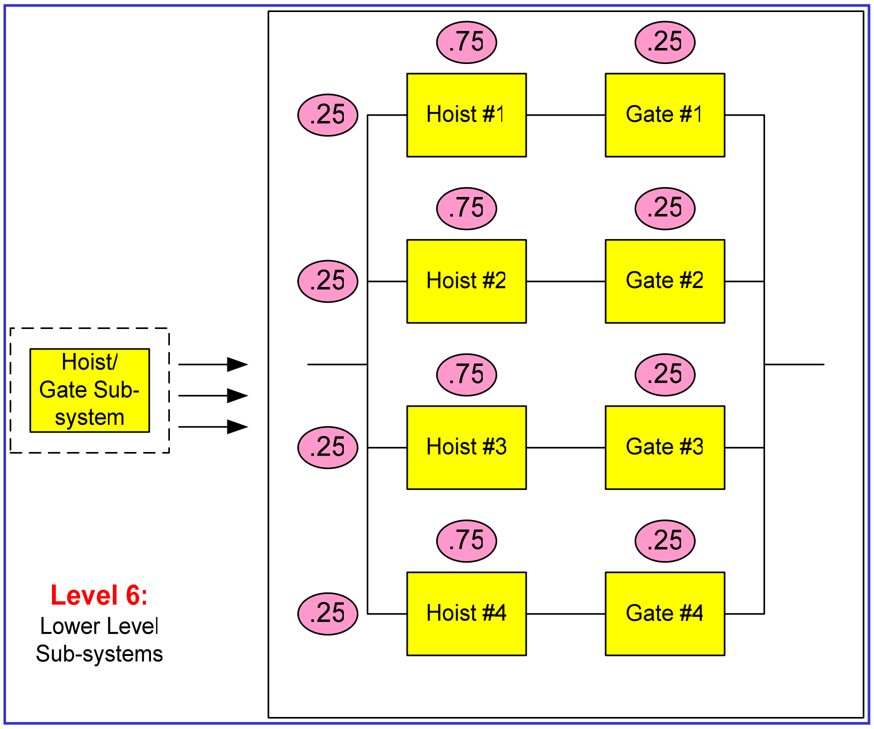


Figure 5.3. The hoist/gate subsystem modeled as a parallel-series system of the four separate gates which each have a dedicated hoist.

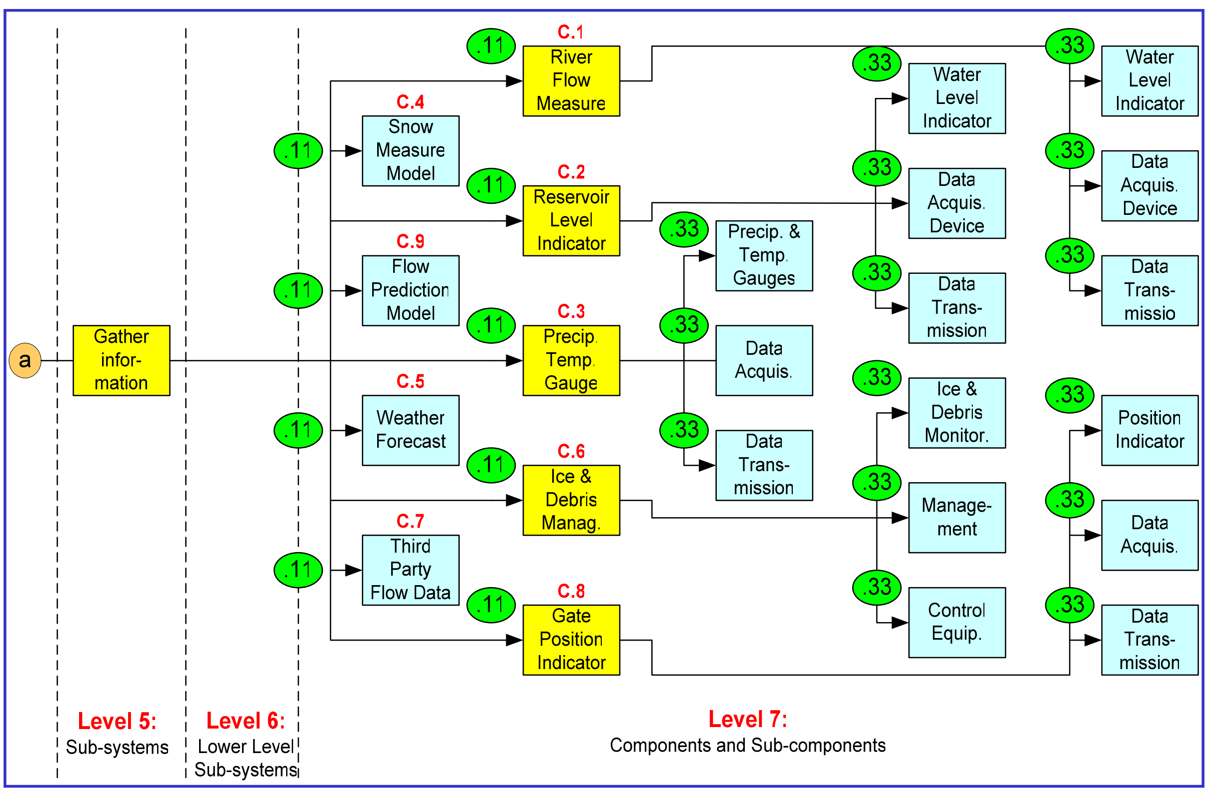


Figure 5.4. Components and subcomponents of the gathering information system on the Great Falls spillway.

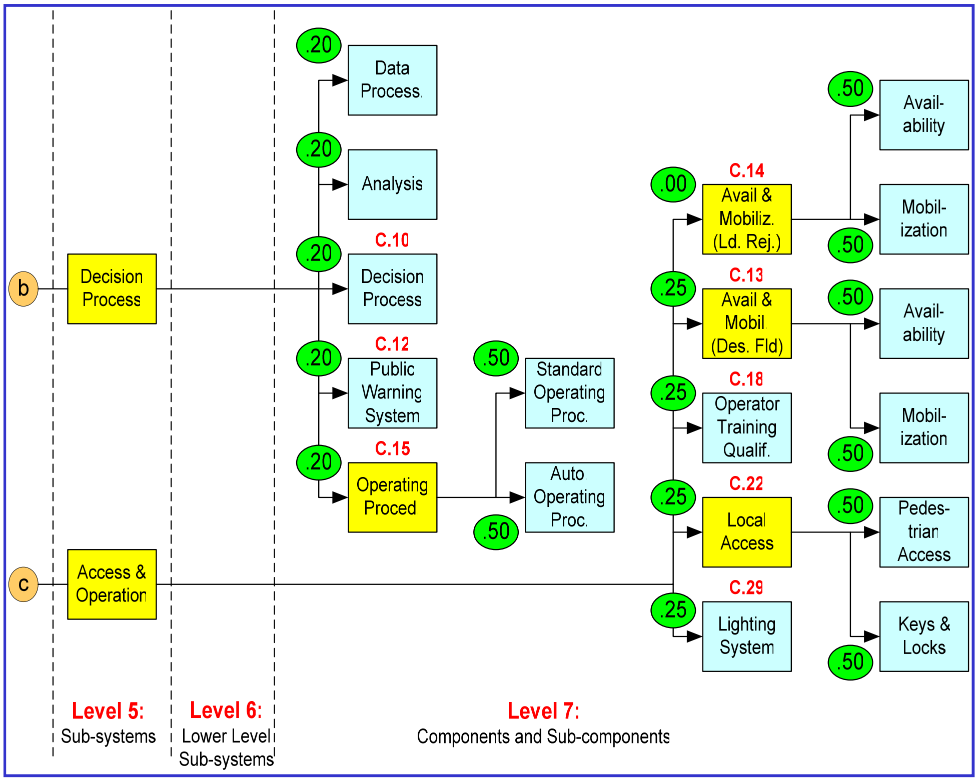


Figure 5.5. Components and subcomponents of the decision process and the access and operations systems on the Great Falls spillway.

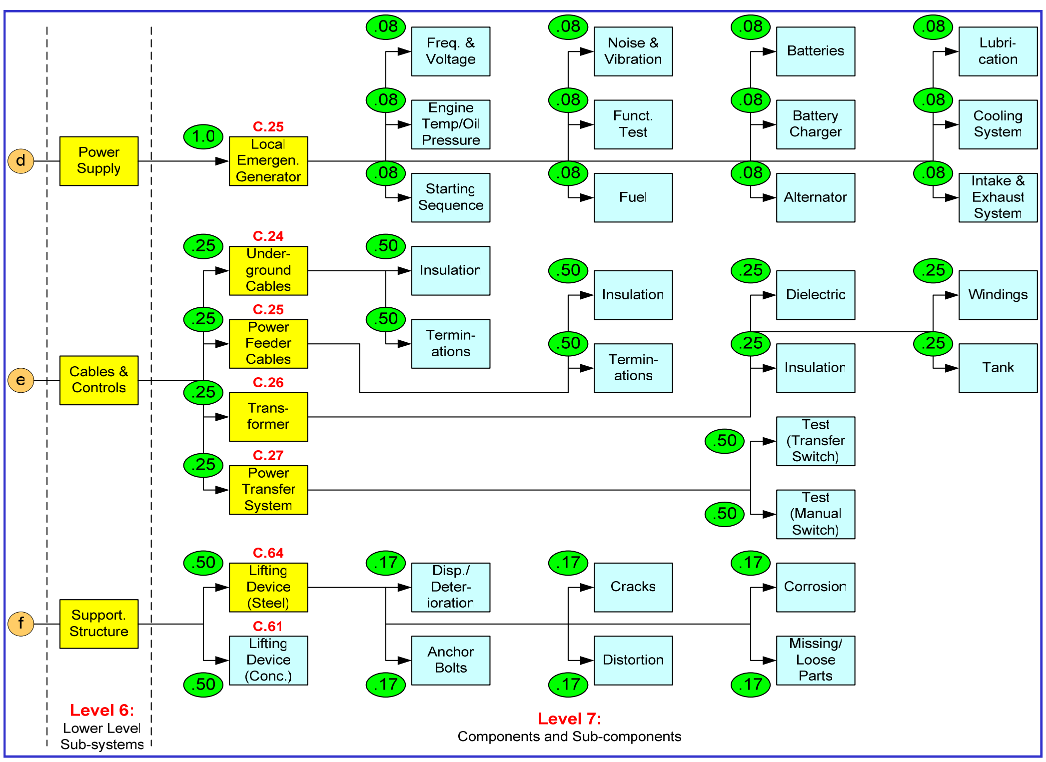


Figure 5.6. Components and subcomponents of the power supply, cables and controls, and support structure systems on the Great Falls spillway.

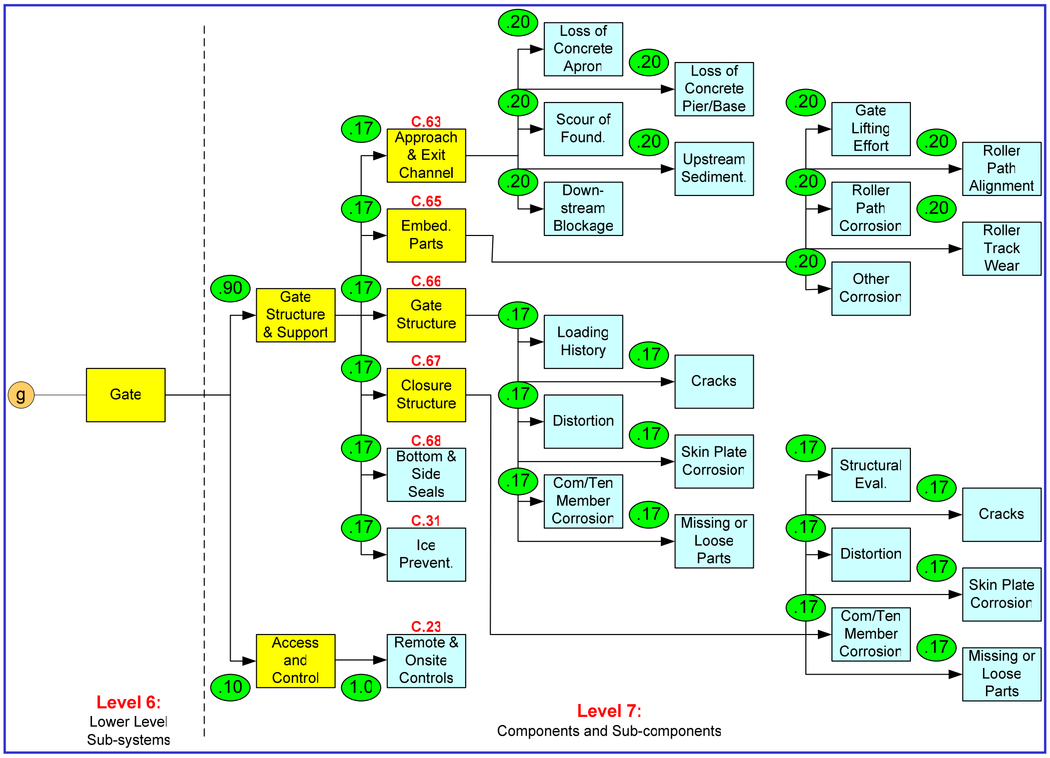


Figure 5.7. Components and subcomponents of the gate system on the Great Falls spillway.

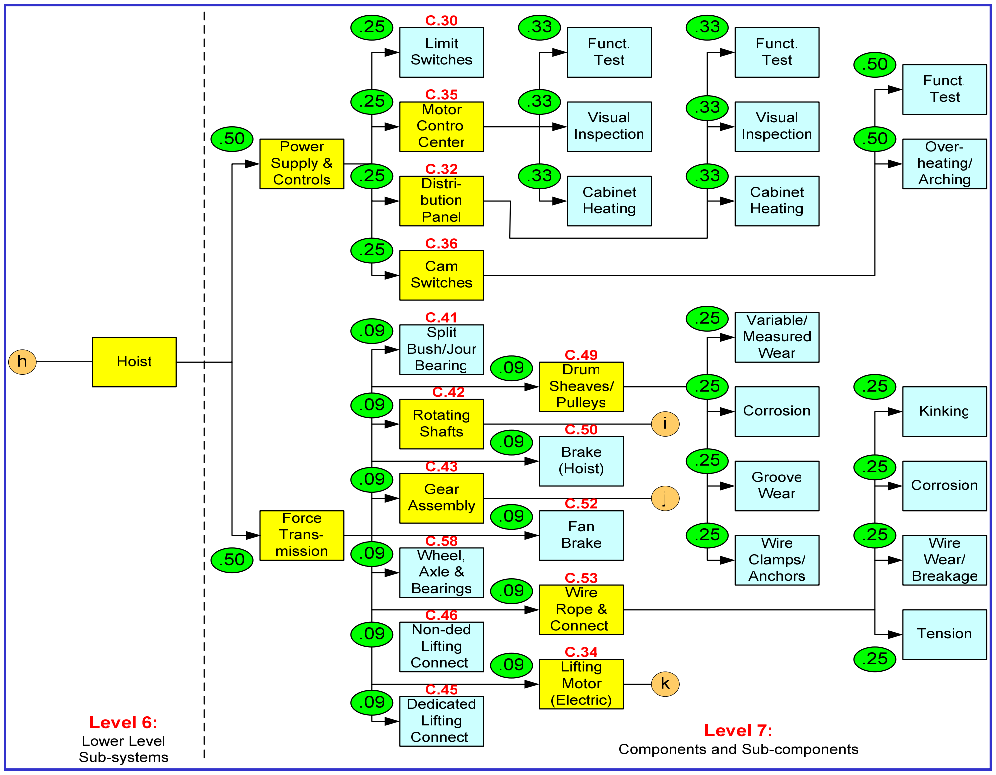


Figure 5.8. Components and subcomponents of the hoist system on the Great Falls Spillway.

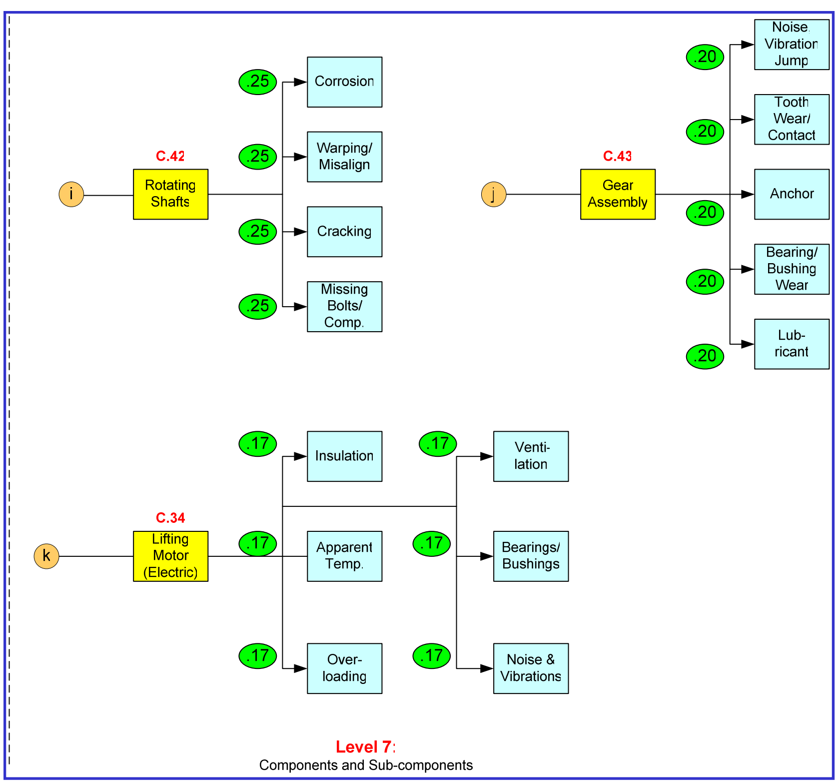


Figure 5.9. Additional components and subcomponents of the hoist system on the Great Falls spillway.

6 Incorporating Structural Vulnerability Into Risk Estimation

6.1 Overview

Security of the nation's infrastructure has become an elevated priority since the terrorist attacks of September 11, 2001. Upgrading the security of various structures has become a major driver of maintenance and rehabilitation funding. The American Water Works Association (AWWA 2003) estimates that the nation's utilities will require $500 million for vulnerability assessments and $1.6 billion for security and protection. The Bureau of Reclamation spent $33 million in 2002 and $53 million in 2003 on vulnerability assessment and security projects for its high-priority dams. This trend indicates that the vulnerability of a structure to terrorist attack may be a relevant consideration in the condition assessment of a structure. The proposed condition index methodology is flexible enough to incorporate any relevant variable, including vulnerability. The purpose of this chapter is to illustrate how structural vulnerability can be incorporated into the development of a structure's CI.

6.2 Incorporating Security into the Condition Index

Using the hypothetical structure shown in Figure 4.4 (see Chapter 4), Figure 6.1 adds a security system to the structure and provides an importance value relative to the rest of the structure. In this example, the importance of security is arbitrarily assigned as I = 0.2. In reality, this value is determined through the same type of analysis that produces the other system importance factors. When adding a vulnerability factor, the importance values for the rest of the structure must be reduced to allow the sum of importance factors at a given level to equal 1.0. Assume the security system was given a rating where the mean CI was 70 and the standard deviation was 7.4. Equation 4.8 (see Chapter 4) revealed that the original structure's mean CI value was 89.5 with a standard deviation of 3.16

at year 0. Incorporating a security system into the structure with the score indicated, the structural system CI would become:

$$CI_{System,Year0} = (0.16)(85) + (0.48)(92.5) + (0.16)(85) + (0.2)(70) = 85.6 \qquad (6.1)$$

$$\sigma_{System,Year0} = \sqrt{(0.16)^2(7.65)^2 + (0.48)^2(3.83)^2 + (0.16)^2(7.65)^2 + (0.2)^2(7.4)^2} = 2.93$$

As a result of the security rating, the overall structure CI was slightly lower, which would give the structure a slightly higher priority for maintenance upgrade funding. The magnitude of the effect is determined by the importance factor given to security.

The security rating is deliberately kept separate from the rest of the structure to give the analyst the option of easily including or excluding it from the analysis. As with the Great Falls spillway, it would have been easy to separate the equipment system from the operations system if the analyst preferred to consider only the equipment. The security system rating could be treated as a component where a simplistic and subjective high, medium or low rating could form a component condition table. Conversely, security could be treated as a complex and comprehensive system consisting of many components and subcomponents. Figure 6.2 illustrates a sample hierarchical structure for a security system and its components.

The security system is divided into subsystems reflecting the criticality, redundancy, vulnerability and response planning aspects of the structure. The criticality variable accounts for the effects on the community and economy if the structure is immobilized. It could be measured in terms of dollar consequence of destruction, anticipated lives lost, dollar value of commerce lost, or size of population affected. The redundancy subsystem assesses the ability of a single fire, bomb, or power loss to destroy or shut down the entire structure. Alternative power sources, multiple lift gates, or redundant structural members might be critical considerations. Response planning reflects the ability of the community and people on site to respond to an attack, and it is further subdivided into internal and external capabilities. Internal planning capabilities measure the capability of the site personnel to respond, and it would be assessed using criteria such as response standard operating procedures, training programs, internal drills and rehearsals, redundant and reliable communication equipment, early warning procedures, detection capabilities, alarm systems, and reporting procedures. External planning assesses the response capability of the outside community, to include law enforcement, fire fighters, medical teams, and local, state, and Federal response teams. Access and distance to the site are also included.

Structure vulnerability refers to the ease with which the site can be attacked. Figure 6.2 classifies vulnerability in terms of air, water, land, and cyberspace. Attack from the air might include dispersal of chemical or biological agents, dropping a bomb, or flying an airplane into the structure. The air vulnerability assessment would be a function of local air defense, air traffic patterns, and ability of the structure to withstand an impact. For dams, a water attack might include assault by watercraft or simply the ability of a terrorist to float an explosive device downstream. Water vulnerability would be assessed by protective measures such as boat patrols that could observe and intercept attacks, observation capability, and capability of the structure to withstand such an attack. Cyberspace vulnerability would depend on the structure's degree of reliance on computers and networked systems. Cyberspace vulnerability encompasses the physical security of the computer systems, redundancy, physical access to workstations, access via telecommunications and wireless devices, and the use of firewalls, intrusion detection devices, and password protection.

Attacks over land are probably the greatest threat. The land subsystem is divided into the power supply, communications and site security lower-level subsystems. The site security subsystem consists of access, observation and presence subcomponents. Access measures the ability to control who is allowed on the site. It might include a perimeter fence; keys or badges to control access; locks on doors and gates; procedures for contractors, deliveries, or tour groups; and intrusion-resistant doors and windows. Observation incorporates the ability to see and detect any terrorist activity. The existence of lighting systems, video cameras, and security patrols would enhance situational awareness. Along the same lines, motion detectors, access control, and, in high-threat situations, chemical alarms, radar systems, and bomb-sniffing dogs would detect potential dangers. A project at an isolated location may be more vulnerable to intrusion because it is farther from the watchful eye of the general public. Figure 6.3 shows examples of security devices currently in place on locks and dams.

Finally, presence measures the degree to which site personnel are available to protect the site. The lowest level of the hierarchy contains an inspectable item with a component condition table that the inspector uses match the observed situation to the best description on the table. Table 6.1 suggests a sample component condition table for the site presence component of the site security component. In this example, the CI score for presence is a function of hours of operation, guards on site, and the hiring of a security manager. Using the same scoring approach outlined in Chapter 3, the security system CI score is a function of the inspection CI scores and importance factors of all the subsystems that comprise the system.

The security system described here is a generic example reflecting many possible configurations. The Corps of Engineers has invested in the Risk Assessment Methodology for Dams (RAM-D), whose purpose is to identify and counteract potential security threats to the nation's 75,000 dams (Matalucci 2002). The results obtained from RAM-D analyses could be incorporated into a probabilistic CI rating system. Whatever method is used to evaluate the security and vulnerability status of a structure, it appears that it could readily be incorporated into a CI assessment if the manager believes it is relevant.

Table 6.1. Sample component condition table for the site presence subcomponent of the site security component of the security system for the hypothetical structure in Figures 6.1 and 6.2.

Site Presence								
Function								
Excellent	Sufficient personnel on site at all times to observe and deter potential threats							
Failed	Site has insufficient personnel to provide adequate awareness of threats							
	0 -- 9	10 -- 24	25 -- 39	40 -- 54	55 -- 69	70 -- 84	85 -- 100	Comments
Indicator	1	2	3	4	5	6	7	
(1) 24 hour operations; personnel constantly on site; (2) dedicated security manager; (3) guards posted at gates							X	
(1) 24 hour operations; personnel constantly on site; and either (2) or (3) above						X		
(1) 24 hour operations; neither (2) nor (3) from above **OR** personnel on site during normal duty hours but gate guards have 24 hour presence					X			
personnel on site only during business hours; no gate guards or security manager			X	X				
site is unmanned, but located in a populated area		X						
site is unmanned and located in a remote area	X							

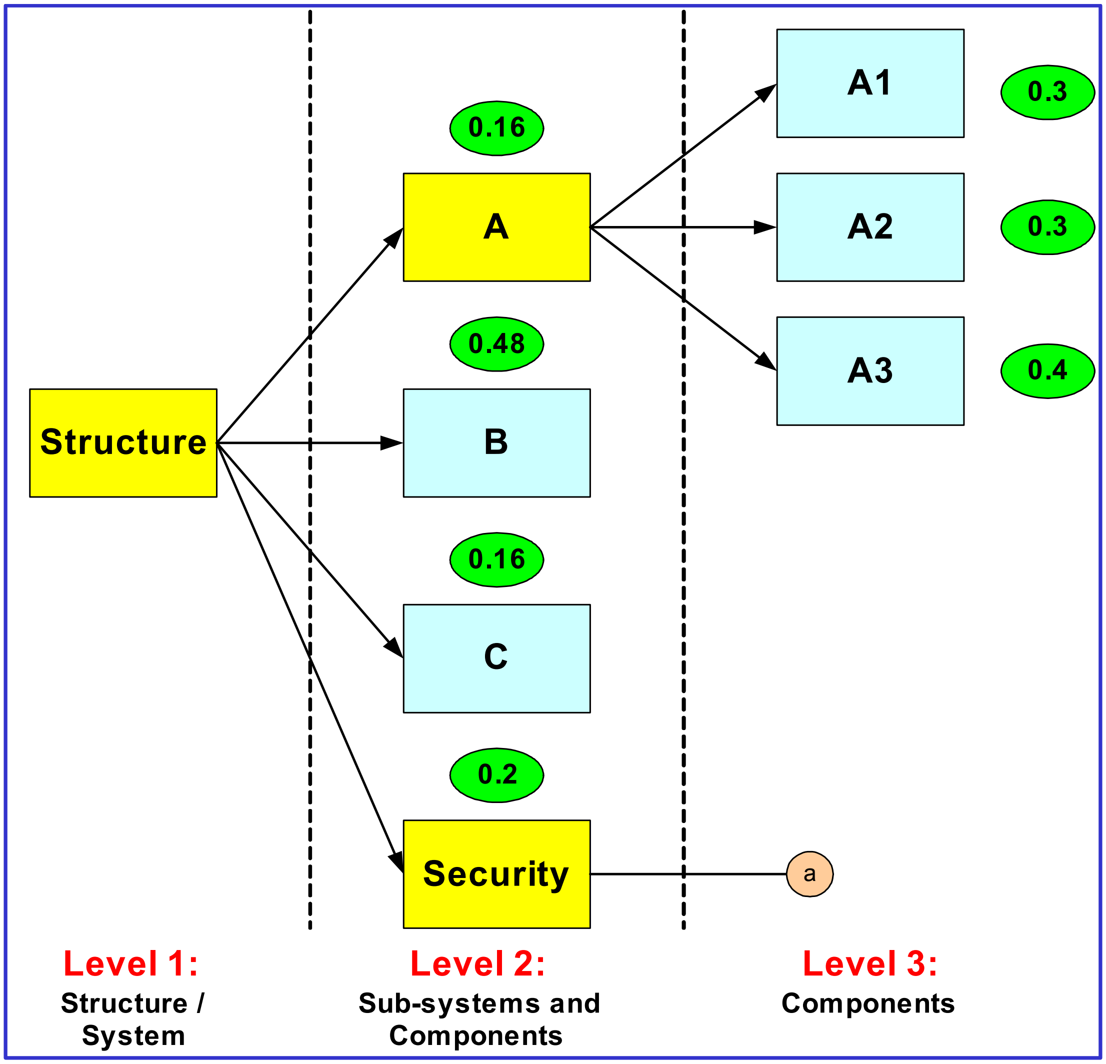


Figure 6.1. Structural hierarchy of the hypothetical structure from Figure 4.4 where a security system is included in the CI analysis.

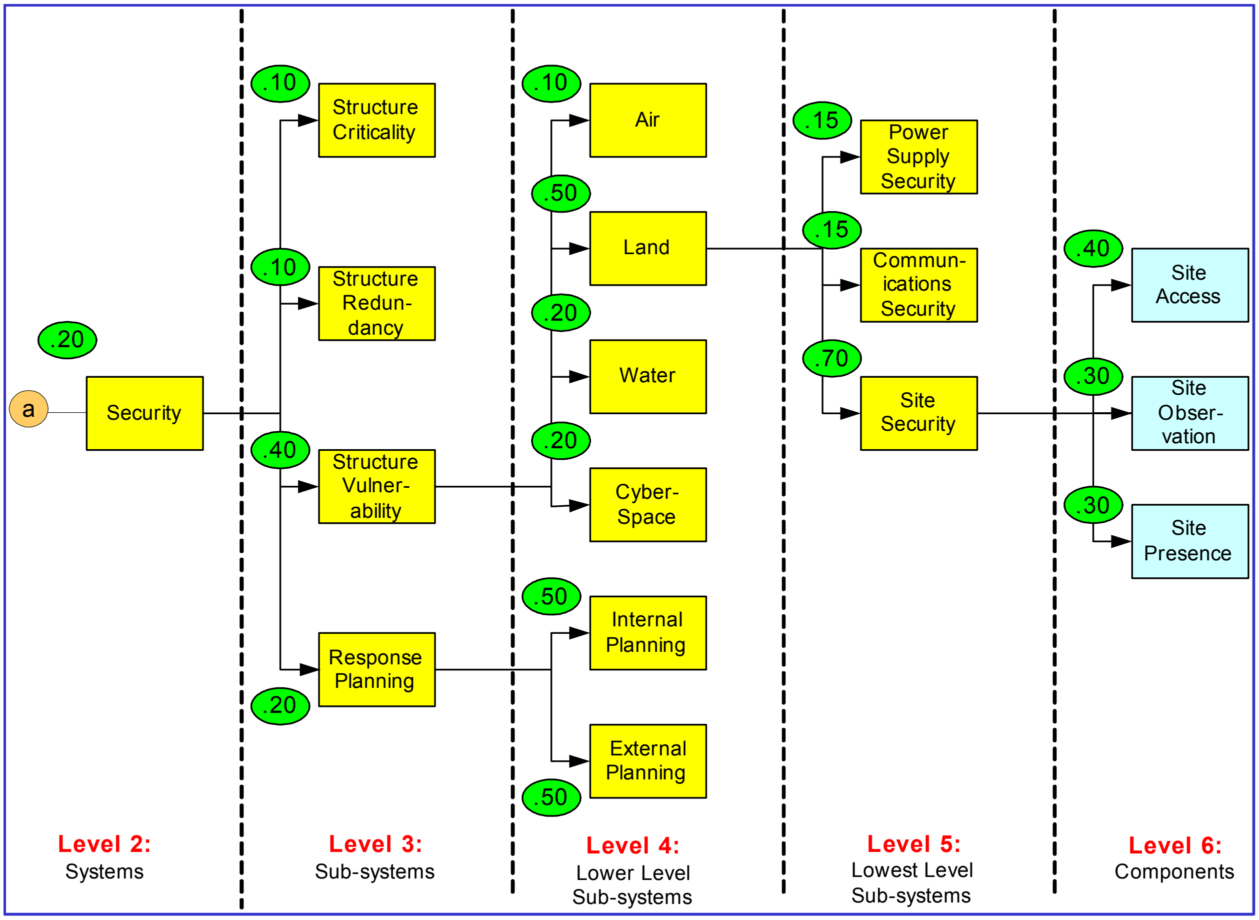


Figure 6.2. Security system for hypothetical structure showing selected subsystems and components.

a.


b.


c.


d.


Figure 6.3. Lock and dam security measures, including coded locks (a), intercom and alarm systems (b), closed-circuit cameras and lighting systems (c) and observation tower (d).

7 Conclusions and Recommendations

7.1 Conclusions

This report has introduced a probabilistic approach for CI assessment of structures that will allow a type of risk-based analysis using periodic visual inspection results. A proposed methodology was introduced using a simple hypothetical series-parallel structure as an example. It was assumed that all components were statistically independent, normally distributed random variables, and that any structure can be described as a hierarchy of systems, subsystems and components. Higher-level CI values were obtained from component inspection results and the relative importance of components to the overall structure. A reliability index and probability of failure were computed at various points in during the service life of a hypothetical example structure along with a cost/benefit analysis using the hazard function. Examples showed that inaccurate initial assumptions can be corrected or updated over time using live inspection data as it becomes available.

The probabilistic CI methodology was applied to spillways on dams using Chouinard et al. (2003) as the source for the structural hierarchy, importance factors, and component condition tables. The proposed approach was applied to the Great Falls spillway using real-world inspection data. The differences between treating the structural system as a composite or weighted average of its components versus the traditional system reliability analysis of series and parallel systems were illustrated and discussed. It also was illustrated how structure security and vulnerability issues could be incorporated into the proposed methodology.

Based on the assumptions used in this study, a risk-based analysis using the well established concepts of a reliability index, probability of failure, hazard function, and cost/benefit analysis is possible and practicable. It is concluded that the probabilistic CI methodology demonstrated here is flexible enough to accommodate any relevant variables, even if they are difficult to quantify. It allows a risk-based analysis of overall structural condition that can be used to compare maintenance and rehabilitation funding priorities among two or more facilities with differing needs.

There are numerous benefits to the methodology proposed in this report:

- It presents the opportunity to use risk-based methods on lower-value structures where such methods could not previously be justified.
- Because the methodology is based on the deterministic CI methods already published, any existing inspection data compiled using such methods can be applied without modification using the techniques described in this report.
- The strict hierarchical form used to describe a structure allows the analysis easily to be broken down by component, and portions of the structural system can easily be excluded or included based on the judgment of the analyst. All levels of the hierarchy are visible making it easier to identify which components most affect a system rating and to evaluate alternatives for replacing components versus replacing an entire structure.
- The inspector is only required to choose the appropriate condition state for a component based on the component condition tables. The actual CI mean value is determined by how long the component has been in that condition state. This method eliminates the need for the inspector to determine a specific CI value, which can be highly subjective and lead to different findings by different inspectors, especially if the condition state includes a large range of values. Therefore, the proposed method will provide greater consistency among inspectors.
- In a deterministic approach, the CI rating is given the same credibility whether the range is 85 – 100 or 25 – 100. Using the probabilistic approach, the uncertainty is quantified by the standard deviation associated with the condition state. That standard deviation is determined by the CI range of the condition state and the assumed capability of the inspector.
- The linear transition of a component through a condition state accounts for the effects of aging. The mean value of the CI gradually transitions from the middle of the condition state to the lowest value in the condition state while the standard deviation remains the same. The component that has been in a given condition state longer will be more likely to receive the maintenance funding.
- By assuming that components are statistically independent and normally distributed, the numerical computations are simplified as compared with traditional reliability analysis. The methodology is only slightly more complex than the deterministic approach and can readily be implemented in a standard spreadsheet application.

- The methodology can be applied to virtually any structure.
- Any relevant variable can be included in the analysis if one can effectively estimate its relative importance to the rest of the structure. Even variables that are difficult to quantify numerically can be used effectively.
- Even when initial assumptions about condition state deterioration are incorrect, they can readily be updated using the exact same data produced through the routine inspection process. If inspections are sufficiently frequent there will be enough time to incorporate actual data and revise the life-cycle maintenance projections to reflect actual conditions. As a record of replacement data is developed, even the probabilistic definition of failure can be updated and revised.
- The structural system CI ratings provide an effective means for comparing the relative conditions of structures that are experiencing very different distresses. It is also an excellent means to communicate the condition of the infrastructure in a standardized way for purposes of funding and public safety.

To summarize, this probabilistic approach offers everything the deterministic condition indexing approach offers and also provides the capability to estimate risk. Because the proposed approach places no additional burden on the inspector, there is no additional overhead involved in replacing the deterministic procedure with this methodology. However, the probabilistic methodology is subject to a number of limitations that need to be considered and may merit further study:

- This probabilistic methodology is based on no hard data. The definition of failure and the assumed capabilities of the inspectors are essentially educated speculation. Real data are only available over time, based on actual performance. Because few lock and dam facilities are closely similar in design and configuration, it may be impossible ever to accumulate a statistically significant database.
- The assumption that condition states are statistically independent and normally distributed may not be correct. Large portions of distributions for condition states will extend outside the 0 – 100 range, as shown for CS1 and CS4 in Figure 4.5. Given the inherent limits to the accuracy of this methodology, this limitation should not have a serious effect on the results. The largest errors will apply to those extreme condition states where the component is clearly safe or clearly failed. The more critical issue is that with independent components, the standard deviation of the CI becomes progressively smaller at successively higher levels of the hierarchy. Therefore, the assumption is not conservative and consequently it poses its own risks. Further study is warranted.

- The methodology lacks a 'red flag' function to indicate that an independent analysis and deliberate repair/no repair decision is needed whenever an inspected item receives a CI score less that 40. Without such a flag, analysts who focus on system-level CI data will overlook minor failures that need prompt attention.
- Assumptions about inspector capability will be very difficult to verify or update.
- The weighted average system CI proposed here does not follow the rules of traditional system reliability analysis and will therefore generate controversy within the community of practice. Traditional system reliability analysis can provide the probability that something in the system will fail, but it cannot account for component importance and it requires an analysis of correlation between failure modes. The system-level CI proposed here indicates the probability that an entire structure has deteriorated to the point that it will be replaced or rehabilitated. That claim has not been proven, however, and the differences between these system reliability approaches will inevitably cause confusion.
- The proposed methodology is not a replacement for a traditional reliability analysis. It does not address the loads, stresses, deformation, size of fatigue cracks, or moments of inertia that are required for commonly accepted capacity/demand reliability analysis. This limitation implies that there may be a substantial difference in the results of cost/benefit analyses using each approach. The nature and size of that difference is beyond the scope of this report.

7.2 Recommendations

Based on the capabilities and limitations discussed in this report, the following recommendations are made for further study and action:

- This report only outlines a methodology and illustrates it on a sample structure. The study should be continued by applying the methodology to a single type of structure for which CI methods have been developed, such as miter gates, spillways, or hydropower structures. The objective would be to determine any procedural modifications needed to address similar structures in different locations. A comparison of inspection results from various structures would provide a benchmark for assessing the validity of the methodology. Participation by actual inspectors will result in the best suggestions for improvement and will either verify or contradict the assertion that this methodology produces more consistency among inspectors than one which employs specific CI values. If real-world CI data are available, it could be included in a time-dependent assessment of an actual structure. (The analysis of the Great Falls spillway covered only a point in time.) Also, a traditional reliability analysis and a probabilistic CI analysis both should be done on a single structure and the results compared, which would provide insight about which approach is more appropriate for a given situation.

- Because the methodology appears to be applicable to any type of structure, it would be beneficial to study its applicability to other Civil Works structures as well as highway bridges and buildings.
- The standardization of CI methods for different structures is aided tremendously through the use of a consistent system in which CI values range from 0 – 100 and the general definition of ranges is consistent. Similarly, the concept of a structural hierarchy should be consistent for all structures. The Corps of Engineers has invested in CI systems for different structures developed by different researchers using somewhat different approaches. The Corps should evaluate those approaches and attempt to standardize the basic methodology to the greatest extent possible.
- Foltz, Howdyshell, and McKay (2001) indicate that CI use throughout Corps districts has been sporadic. Some Districts use CI inspections in a half-hearted manner and some do not use them at all. The only way for an effective database to ever be established is for every District to conduct CI inspections on a periodic basis and report the results to headquarters where they can be consolidated, evaluated and used. The Federal Highway Administration provides an excellent model in its requirements for inspection and reporting of condition on the nation's highway bridges. To repeat the recommendation made in Estes (2003), the Corps of Engineers should make a commitment at the highest level to require all Districts to conduct CI inspections and then continually consolidate and the publish the results. The initiative could be phased in over time starting with a specific type of structure. The inevitable bugs could be worked out at a smaller level before incorporating more structures.
- Independent review of this report produced the following recommendations, which are similar to the recommendations of the authors:
  - The values of CI should first be collected for a large set of structures.
  - The statistical parameters of this random variable CI can then be calculated.
  - A target value for CI can be fixed based on the concept of expert systems.
  - Then, the probability of failure can be calculated with a modified form of Eq. 4.1 using the CI- target value.

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14. ABSTRACT
Inland waterways maintained by the U.S. Army Corps of Engineers carry about 17% of the nation's intercity cargo, so service interruptions related to waterway infrastructure failure can cause substantial economic loss. Maintenance and repair (M&R) requirements for navigation structures compete for funding with every other national priority, however, and Federal budgeting decisions are determined largely on the basis of net benefit to the nation per dollar invested. The Corps uses analytical tools and methods to help objectively determine project benefits versus costs. In Corps cost/benefit analyses for navigation structures, reducing the risk of failure through repair or rehabilitation is quantified as a benefit. Conventional reliability-based risk analysis is costly and complex, however.

This study investigated the adaptation of an existing condition indexing (CI) methodology to assess overall structural risk and failure probability. It was concluded that a risk-based analysis, using the well established concepts of a reliability index, failure probability, hazard function, and cost/benefit analysis, is possible and feasible. Because CI data have not been systematically collected and are not available, the methodology proposed here remains untested. A number of reasonable assumptions made in this study have not yet been verified using actual CI data collected over time from existing projects.

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