APPENDIX D

INTRODUCTION TO AN ASSESSMENT OF STRUCTURAL RELIABILITY

D-1. Introduction. The objective is to introduce methodology to be used to evaluate the reliability of civil works structures for various modes of performance. These reliability measures are intended to be used in analyses for prioritizing structural rehabilitation. The results of a reliability analysis are used to provide a condition ranking of the structure or component. Basic references are provided herein. A decision making flow chart is provided as Figure D-1, and reporting requirements for reliability analyses are presented in paragraph D-8.

a. Traditionally, evaluations of structural adequacy have been expressed by safety factors. A safety factor can always be expressed as the ratio of capacity to demand. The safety factor concept, however, has shortcomings as a measure of the relative reliability of structures for different performance modes. A primary deficiency is that parameters (material properties, strengths, loads, etc.) must be assigned single, precise values when the appropriate values may in fact be uncertain. The use of precisely defined single values in an analysis is the **deterministic** approach. Thus, the safety factor reflects both the condition of the structure and the engineers' judgement and degree of conservatism in assigning values to parameters.

b. The **probabilistic** approach extends the safety factor concept to explicitly incorporate uncertainty in the parameters. This uncertainty can be quantified through statistical analysis of existing data or judgmentally assigned. Even if judgmentally assigned, the probabilistic results will be more meaningful than a deterministic analysis because the engineer provides a measure of the certainty of his or her judgement in each parameter.

D-2. Basic Principles.

a. Random Variables. In the probabilistic approach the parameters are treated as random variables. Random variables assume a range of values in accordance with a function termed a probability density function or probability distribution. Although the value of a parameter is uncertain or variable, the probability density function quantifies the likelihood that the value of the random variable lies in any given interval. When parameters are defined as random variables, functions of these parameters such as safety factor also become random variables and can be expressed in probabilistic terms.

b. Probability of Unsatisfactory Performance. An engineering reliability analysis determines the probability of unsatisfactory performance, Pr(u), defined as the probability that the value of a function which characterizes the performance of the system exceeds some limit state. These performance functions, or performance modes, are deterministic functions which are used in design or analysis and should define reasonable performance levels expected to occur over the service life of the project or component. Failure modes for civil works type structures are difficult to define deterministically, however, and describe a condition which is unacceptable for USACE projects, i.e., failure of a structure or component. Therefore, performance modes such as calculation of deflections, cracking or loss of section which can be more readily defined deterministically are used in order to detect adverse conditions prior to failure.

c. Limit States. Limit states define the point at which the performance function predicts that unsatisfactory performance will occur, or that the engineering consequences will have some adverse economic impact. Several limit states may apply to a particular performance function. For example, the limit state for deflection of a gravity lock wall monolith could be taken as the event representing excessive lateral movement which causes cracking, spalling or binding of operating equipment. Several loading conditions and the corresponding deflections may be required to be calculated to determine the range of deflections, their impact upon the operating equipment, barge traffic and stability, in order to establish limit states.

d. Reliability. The reliability, R, is the probability that the unsatisfactory performance, Pr(u), will not occur. Mathematically reliability is determined as follows:

$$R = 1 - Pr(u).$$

e. Safety Ratio. A concept used in the calculation of reliability is the safety ratio. Important parameters should be defined as random variables, then the total capacity, C, (resistance) and the total demand, D, (load) are also random variables. The safety ratio, SR, is the quotient of the capacity and demand; or of the resistance and load. The probability of unsatisfactory performance can then be expressed as the probability that the safety ratio will be less than one, or:

$$Pr(u) = Pr\,(SR<1) = Pr[(C/D) < 1]$$

D-3. Calculation of Probability of Unsatisfactory Performance.

a. Methods. Four methods are available to calculate the probability of unsatisfactory performance; (1) Reliability Index, (2) Hazard Function, (3) Historical Frequency of Occurrence, and (4) Expert Elicitation (or subjective probabilities). The selection of the method to be used to establish the probability of unsatisfactory performance will depend on the type of component or structure, availability of project specific data and the level of study. Each of these methods are briefly discussed below.

b. Reliability Index. In many applications of reliability analysis, the probability of unsatisfactory performance is discarded in favor of the reliability index, β, which is a measure of how much the expected average value of the safety ratio exceeds the limit state at a particular point in time. A β value of 3.0 implies that the expected value of the performance function lies three standard deviations above the limit state and structures, components and performance modes with higher indices are considered to be more reliable than those with lower indices. Expressing reliability in terms of the reliability index has several advantages:

(1) A reliability index can be calculated knowing only the means, standard deviations and correlation coefficients of the variables.

(2) Analysis of recurring events and replicate components (such as failure of mechanical parts or electric power), have a measurable and easily understood frequency of failure. Many features of navigation structures are uniquely adapted to site conditions and are not expected to fail due to foreseeable rare events, (i.e., observations and analyses can be made and some remedial action will be undertaken before the reliability drops below a tolerable value).

(3) Reliability index approach is consistent with recent structural design codes and techniques used for highway bridge evaluation.

The reliability index is converted to a probability of unsatisfactory performance for the assumed distribution of the performance function. The probabilities determined in this manner are relative probabilities considered to be adequate for ranking of investment priorities and should not be confused with absolute measures of probability required for making safety decisions, nor are the probabilities time-dependant. This procedure yields the reliability at a particular point in time, or a snapshot of the current reliability, and assumes that the component has survived up to that time. In order to determine the time-dependent nature of reliability as hazard function analysis must be conducted.

c. Hazard Function. The reliability of a component or structure changes with time due to environmental impacts, stress history and operational history. Therefore a time-dependent reliability analysis should be conducted. While the reliability index approach outlined above represents an approximation of the reliability at a point in, hazard functions more accurately predict the reliability of degrading structures. The hazard function, or conditional failure rate, is the probability that the component will survive in the next, or given, time period assuming it has survived up to that time. The hazard function h(t) is expressed mathematically as a function of the reliability function L(t) as follows:

$$h(t) = -\frac{\partial \ln L(t)}{\partial t}$$

d. Historical Frequency of Occurrence. Probabilities of unsatisfactory performance may be established by examining historical data and/or test data. If the historical record is of sufficient length and the sample size for the particular component and event under consideration is large enough, historical rates of unsatisfactory performance may be generated by statistical analysis of the data. Care must be exercised to ensure that the data used is applicable for the event and performance mode under consideration. This is generally not the case for civil engineering structures, i.e., the length of record is short and the sample size is small. Data and sample size may be sufficient, however, for smaller components such as motors, electrical parts and mechanical equipment, or industry data of testing on such items may be available. Survivor curves have also been used to establish probabilities of unsatisfactory performance based upon historical data. These curves are generated for specific types of electrical and mechanical equipment, and show the number, or percentage of the total population, surviving as a function of time. An analysis of the survivor curve for the particular type of equipment under consideration can yield the probability of unsatisfactory performance in the next time period and in future time periods. Care must be exercised in applying survivor curves to a particular piece of equipment to insure that the survivor curve chosen is based upon the same operating and maintenance conditions as have been experienced in the field. ETL 1110-1-337 and guidance on the application of survivor curves to hydropower equipment are available from the Hydroelectric Design Center (CENPD-PE-HD).

e. Expert Elicitation. Expert Elicitation is the use of expert judgement to establish subjective probabilities to measure an individual's degree of belief concerning the likelihood of the occurrence of an event. Subjective probabilities are generally used whenever there is insufficient data to develop the probability of an event from its historical frequency of occurrence or to conduct an analytical assessment of the probability. The method is highly dependent upon the experience and skill of the panel of experts selected and the procedures used to avoid biases in the probabilities. The procedure is primarily used for events which have a probability of occurrence between 0.1 and 0.9 since rare events with very low probabilities are more vulnerable to bias. Methods are available to reduce this bias; however, they increase number of events which must be analyzed and the time required by the expert panel. Guidance concerning the use of expert elicitation should be obtained in consultation with CECW-ED.

D-4. Analysis Procedures. Guidance for conducting reliability analyses using hazard functions, historical frequencies of occurrence and expert elicitation are available from various sources in the literature and upon consultation with CECW-ED. The reliability index provides a means to express reliability as a function of the means and standard deviations of C and D, where C and D are functions expressing the capacity and demand associated with the performance mode. A reliability index based analysis for a typical mode of performance should be conducted in accordance with ETL 1110-2-532.

D-5. Overall System Reliability. Reliability for a number of components or a number of modes of performance, may be used to estimate the overall reliability of a structure. To gain insight into this approach, consider two extreme cases, the series system and the parallel system.

a. Series System. In a series system, the system will perform unsatisfactorily if any one component performs unsatisfactorily. If a system has n components in series, the probability of unsatisfactory performance of the ith component is p_i and its reliability, $R_i = 1 - p_i$, then the reliability of the system, or probability that all components will perform satisfactorily, is the product of the component reliabilities:

$$R = R_1R_2R_3....R_n = (1-p_1)(1-p_2)(1-p_3)...(1-p_n)$$

b. Simple Parallel System. In a parallel system, the system will only perform unsatisfactorily if all components perform unsatisfactorily. Thus, the reliability is unity minus the probability that all components perform unsatisfactorily, or:

$$R = 1 - p_1p_2p_3....p_n$$

c. Parallel and Series Systems. Solutions are available for systems requiring r-out-of-n operable components, which may be applicable to problems such as dewatering with multiple pumps, or closing a gate bay with emergency bulkheads. Subsystems involving independent parallel and series systems can be mathematically combined by standard techniques.

(1) Upper and lower bounds on system reliability can be determined by considering all components to form parallel and series systems, respectively; however, the resulting bounds may be so broad as to be unpractical. A number of procedures are found in the references to narrow the bounds.

(2) Civil engineering systems such as locks and dams (or even building frames) are complex and may have many performance modes. Some of these may not be independent; for instance several performance modes may be correlated to the occurrence of a high or low pool level. Earth pressures, sliding, and overturning performance are all correlated to shear strength. Rational estimation of the overall reliability of a lock and dam is a topic that is undergoing further research.

d. A Practical Approach. In many systems, the reliability of a few subsystems or components may govern the reliability of the entire system; navigation systems and hydropower plants are no exception. Thus, developing a means to characterize and compare the reliability of these components as a function of time are sufficient to make engineering judgements to aid in prioritizing O&M expenditures.

(1) For steel design, major structural components are designed to a constant value of the reliability index, typically about 3.0; however, connections are designed to higher reliability index values, perhaps 5.0, as engineers have always desired to avoid problems at connections. A complex steel frame is designed such that each component meets a target reliability index value, which may vary, but a "system reliability" calculation is not routinely done in building design. However, target reliability indices may be established for critical lock and dam or hydropower components and performance modes, and O&M priorities will be directed at ensuring that these targets are met or exceeded.

(2) For initial use in reliability assessment, the target reliability values presented in Table D-1 should be used. A hazard function plot of reliability vs time for major performance modes should be developed. The objective of the Operation and Maintenance program would be to keep the reliability for each significant mode above its target value for the foreseeable future.

D-6. Target Reliability Values. Reliability indices are a relative measure of the current condition and provide a qualitative estimate of the structural performance. Structures with relatively high reliability indices will be expected to perform their function well. Structures with low reliability indices will be expected to perform poorly and present major maintenance problems. If the reliability indices are very low, the structure may be classified as a hazard. Working from a sufficiently large experience base, it should be practical to make some estimates of expected structural performance with some engineering judgement. A large experience base exists within USACE and studies are planned to collect, organize and analyze these operation and maintenance records. The target reliability values shown in Table 1 should be used in general. Case-by-Case refinements should be conducted in consultation with and approved by CECW-ED.

D-7. References.

a. AISC, Load & Resistance Factor Design, Manual of Steel Construction, 1st Edition 1986, AISC.

b. Beim, G.K. and Hobbs, B.F., June, 1995, Development and Use of Subjective Probabilities and Event Trees for Water Resources Investments, Draft report to CEIWR, Ft. Belvoir, VA.

c. Benjamin, J. and C.A. Cornell, (1970) Probability and Statistics, and Decision for Civil Engineers, McGraw-Hill, New York.

d. Ellingwood, Bruce R., Engineering Reliability and Risk Analysis for Water Resources Investments: Role of Structural Degradation in Time-Dependent Reliability Analysis, Contract Report ITL-95-3, July 1995, Waterways Experiment Station, Vicksburg, MS.

e. Wolff, Thomas F. and Weijun Wang, Jan. 1992, Engineering Reliability of Navigation Structures, Report prepared under DACW 39-91-C-0041.

Table D-1

TARGET RELIABILITY INDICES

EXPECTED PERFORMANCE LEVEL	BETA 1/	PROBABILITY OF UNSATISFACTORY PERFORMANCE 2/	POTENTIAL PHYSICAL CONSEQUENCES
HIGH MAINTENANCE	5.0	0.0000001	NORMAL
GOOD	4.0	0.00003	MAINTENANCE WITH TRAFFIC MAINTAINED
ABOVE AVERAGE	3.0	0.001	DOWNTIME FOR REPAIRS
BELOW AVERAGE	2.5	0.006	FREQUENT OUTAGES FOR REPAIRS
POOR	2.0	0.023	FREQUENT AND EXTENDED OUTAGES FOR REPAIRS
UNSATISFACTORY REHAB	1.5	0.07	EXTENSIVE REQUIRED
HAZARDOUS	1.0	0.16	EMERGENCY ACTION TO ALLEVIATE HAZARDS

1/ Beta = Reliability Index determined using a lognormal distribution of the performance function.

2/ Probability of unsatisfactory performance is the probability that the value of the performance function will exceed the limit state, or that an unsatisfactory event will occur. For example, if the performance function is defined in terms of miter gate impacts, and the probability of unsatisfactory performance is .023, then 23 of every 1000 impacts will result in damage which causes a shutdown.

D-8. Outline for Reliability Analysis Report. The probability based Reliability Analysis Report (RAR) should be presented in enough detail to fully substantiate the recommended plan. It should contain complete checked computations and should contain the information described in the following paragraphs.

a. Pertinent Information. The RAR should contain all data pertinent to the project or component being evaluated. Pertinent data includes the following:

(1) Color photographs of the component being evaluated. These photographs should be of sufficient detail to clearly indicate the problem being addressed and should be easily identified with respect to the location on the structure.

(2) Repair data including cause of damage, method of repair, cost of repair, and the time in which the structure was out of service to accomplish the repair.

(3) Survey data indicating any observed changes in alignment, and movement of the component being investigated. The movement should be documented to indicate the changes with respect to time. Is the movement increasing with time? The survey data should also indicate changes in the surroundings such as scour, changes in the backfill elevation, or changes in the pool elevation.

(4) Instrumentation data indicating results of pressure meters, inclinometers, joint movement indicators, and piezometers should be included.

(5) Information gathered during the life of the project that indicates a more exact determination of loading than that used in the original design.

(6) Any other data pertinent to the component being investigated; concrete crack mapping, condition index, etc.

b. Analysis. A probability based reliability analysis should be included for the existing (or base) condition of the structure or component and the reliability reported. This should be based on the available pertinent data described above. Also provide the following information:

(1) Tables showing the random variables and constants for each component or feature analyzed.

(2) Tables showing the mean and coefficients selected for each random variable.

(3) Sample calculations showing the modes of performance, reliability calculations, etc. If computerized spread sheets are utilized in the analysis, provide sufficient description of column and row headings to allow for an understanding of the equations used in the spreadsheet.

(4) Tables showing the calibration of the performance functions. Show reliability calculated for the distressed and design components used to calibrate the performance in accordance with paragraph D-3.f(2).

(5) Provide an event tree showing the probabilities of unsatisfactory performance for each mode of performance.

c. Alternative Studies. Alternative schemes for repair and rehabilitation must be fully investigated. Alternatives investigated should include the use of new materials, new repair techniques and innovative designs as well as all reasonable alternative configurations. The schemes investigated must address and resolve concerns which have led up to the major rehabilitation proposal, such as declining reliability and consequences of unsatisfactory performance of the structure or component. Since complete reliability analyses must be conducted on all alternative schemes, only reasonable and technically feasible alternatives should be investigated. This requires a screening process to eliminate less reasonable schemes from consideration. Factors considered in the screening process should include, but not be limited to, technical feasibility, constructibility, and impacts upon appurtenant structures. Alternative schemes eliminated during this process for engineering reasons should be briefly described, along with the factors which resulted in elimination.

d. Recommended Plan. The recommended plan should be selected based upon the results of the alternative studies and should be the plan which offers the greatest benefit to the project not only with respect to economic, but also to restoring project reliability. A copy of the complete reliability analysis for the selected plan should be included in the report.