

Using Reliability-Based Models to Assess Rehabilitation Needs

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Abstract

Due to increasing budget constraints, funding available to maintain, rehabilitate, improve, or replace aging US Army Corps of Engineers (USACE) structures is declining with respect to funding requirements. Therefore, the available funds must be selectively invested to achieve maximum benefits. To compete for scarce appropriation resources, USACE districts are now required to justify civil works rehabilitation project funding by demonstrating a need for improvement in reliability or efficiency. A risk-based benefit-cost model is utilized to establish funding justification. This analysis model requires input to assess the current condition of a structure and its degradation rate. This methodology incorporating both reliability and economic aspects would aid in forming a nationwide planning system.

Introduction

USACE structures provide a vital link in the nation's infrastructure, particularly in the area of inland navigation. Many of these structures were built in the 1930s and 1940s and have exceeded their fifty-year design life and/or capacity. Therefore, major maintenance work is necessary to keep them operational. Many of these lock sites are operating at full capacity and will not be able to meet future projected barge traffic demands. At most of the older locks, tow sizes currently used are generally greater than those expected when the lock was designed. Also, since structures within each particular waterway were generally built at the same time, the problem is compounded for some USACE districts.

Projections indicate that major capital investments will be needed for rehabilitation and efficiency improvement of Corps structures. Presently, allocations for major

projects are provided in the federal budget, with fifty percent being supplied from fuel taxes for inland navigation systems. With the current emphasis to decrease expenditures in the federal budget, available funding will not be sufficient to meet all the Corps' needs.

Objective

A long-term investment strategy is essential for identifying and prioritizing the critical needs within the Corps of Engineers. When investment decisions are considered for these structures, three main areas must be addressed:

- Current operation and maintenance work
- Planning for future rehabilitation work
- Design for future improvements.

The study's initial purpose was to establish a methodology for determining the benefit of rehabilitating a structure at the present time versus later. Included in this analysis would be an evaluation of an engineering system's performance or the likelihood (probability) of a problem occurring. Results of this engineering condition-based evaluation are then used in a risk-based benefit-cost model to determine the optimum decision under the restriction of limited resources. Additionally, the engineering condition-based evaluation would provide a consistent means of comparing the relative reliability of different components of a structure, the relative performance of alternative rehabilitation designs, and the overall reliability of different structures.

Reliability Method

Reliability is defined as the mathematical probability that a system will operate as required. Methods incorporating reliability have been utilized to estimate a

system's lifetime and then relate this lifetime to performance factors. Civil engineers have begun to use reliability analysis procedures to reasonably quantify the expected condition of a system. In probabilistic analysis, the parameters used in calculations are treated as random variables and represented by probability distributions rather than explicit values. Results of this probabilistic analysis may be expressed in the form of a reliability index.

A factor of safety (FS) is traditionally used to measure the safety of structures and their components. For any given performance mode, the capacity (C) and demand (D) functions may be expressed as the FS or safety ratio (SR)

$$FS = SR = C/D \quad (1)$$

Capacity function could be a material's strength or ultimate stress, while applied load or applied stress is represented by the demand function. A structure will perform unsatisfactorily when the demand placed on it exceeds the structure's capacity. When capacity equals demand, the limit state for SR is attained, which can be stated as

$$C/D = 1 \quad (2)$$

In traditional deterministic analysis, components are designed such that the ratio in Equation 2 exceeds unity by some acceptable minimum value, which depends on the problem and the performance mode being investigated.

In probabilistic analysis, uncertainty in capacity and demand can be expressed as a probability distribution for each variable with associated limit states (see Figures 1 and 2). To construct probability distributions,

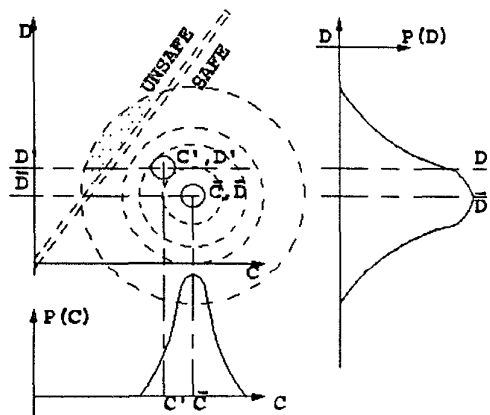


Figure 1. Joint Distribution of C and D

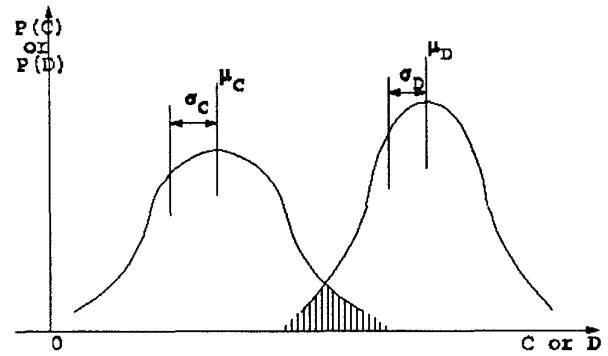


Figure 2. Distributions of Capacity and Demand

one or more of the independent variables from a deterministic analysis are treated as random variables and then the calculations are performed using this range of values rather than a single value. The probability of unsatisfactory performance, $P(u)$, can then be expressed as

$$P(u) = P(C < D) = P(C/D < 1) \quad (3)$$

and the reliability, R , as

$$R = 1 - P(u) \quad (4)$$

Unsatisfactory performance will occur in the shaded area of Figures 2 and 3. Generally, capacity and demand distributions are not known, since the distributions of the input parameters on which they are based are unknown. By determining the mean, μ , and standard deviation, σ , of the input parameters, a mean and standard deviation of capacity or demand may be calculated. A reliability index, β , may be used to

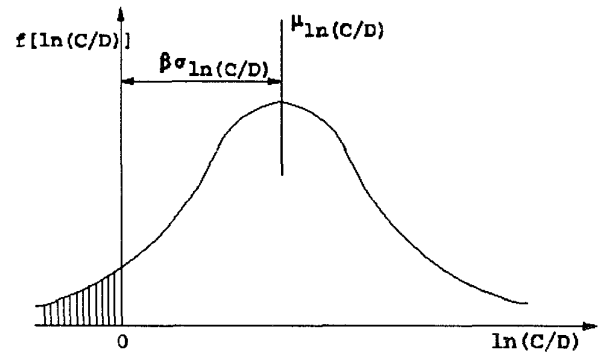


Figure 3. Transformed Lognormal Distribution of C/D

express reliability as a function of the means and standard deviation of capacity and demand. This reliability index may be defined in terms of $E[\ln C/D]$ or $\mu_{\ln C/D}$, and $\sigma_{\ln C/D}$, which are probabilistic moments of a lognormally distributed function (see Figure 3). The reliability index measures how much the expected average value of the SR exceeds the limit state.

Theoretically, moments can be obtained by integrating the performance function over the distribution range of the random variables. In practice, the integration can be approximated using various simulation methods, point estimate methods, or Taylor series approximations. These methods replace the probability distributions of the random variables with the means and standard deviations of the random variables. Approximate integrations by point estimate methods or the Taylor's series approach are attained by performing repetitive deterministic analyses using the various possible value combinations of the random variables.

Sheet Pile Guidewall Example

The application of reliability assessment procedures to an anchored sheet pile guidewall is illustrated using the Brazos River Floodgates (Floodgates) Project on the Gulf Intracoastal Waterway (GIWW) near Freeport, Texas. Locations and layouts of the Floodgates are exhibited in Figure 4. The purpose of the Floodgates is to reduce currents and the deposition of sand and silt in the GIWW as a result of high water stages on the Brazos River. Floodgates are located on each side of the Brazos River and have four separate guidewall sections. These guidewalls are located on the approaches to each gate and function as energy absorption devices in addition to safely guiding the tows through the gate structures. Construction of the existing guidewalls was completed in 1951. A cross-section of a guidewall is shown in Figure 5. Each guidewall is composed of a steel sheet pile wall, backed by earth fill, tied back to anchor walls, and protected by rubbing timbers and tangent plates.

Natural processes have resulted in the current deteriorated condition of the guidewalls. The most severe deterioration of the steel sheet pile is in the splash zone where exposure to salt water and air occurs on a regular basis. Corrosion due to this exposure has reduced the thickness of the sheet piling and often created holes in the piling. Measurements of piling removed from the West Gate guidewalls exhibited losses in metal thickness of about 0.125 in. in areas that were continuously submerged. This rate agrees with

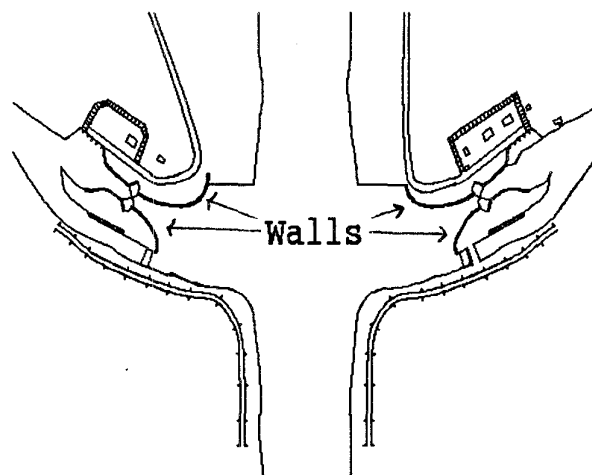


Figure 4. Brazos River Floodgates

predictions of 3.6 mils (1 in. = 1000 mils) per year for piling submerged in saltwater. Water surface differential between the GIWW and the Brazos River seldom exceeds 2 ft. creating significant shoaling and vessel handling problems. Towboat captains periodically lose control of their tows when they encounter the river currents crossing their path, and errant tows often collide with the guidewalls resulting in various degrees of damage to the walls. The loss of metal due to corrosion has decreased the pile's ability to withstand these collisions.

Anchor rods help to hold the piles erect, but their strength and the effectiveness of the fasteners connecting the sheet piles to the anchor rods have been reduced as a result of corrosion. Rods removed from the West Gate guidewalls revealed losses in diameter of

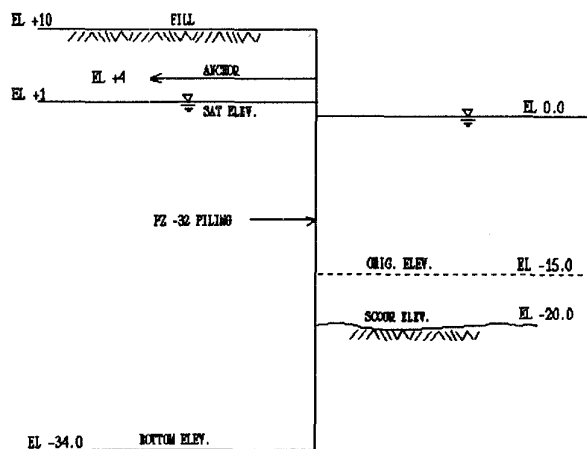


Figure 5. Cross-Section of Guidewall

about 0.2 in. due to corrosion. Exposed anchor rods at the East Gate had localized corrosion of about 0.1 in. near the back face of the guidewall. Approximately 5 ft. of scour at the base of the guidewalls has occurred since they were originally constructed. This scour has lowered the mud line thereby reducing the bending moment in the sheet piling and the load on the anchor rods. Contracts to replace the West Gate guidewalls were awarded in FY 1990.

Based on the 1994 condition of the guidewalls, three modes of unsatisfactory performance could have occurred

- Loss of sheet pile embedment
- Bending of the sheet pile
- Tension in the anchor rods.

For a single time period, these performance modes can be represented by the event tree shown in Figure 6.

For comparison purposes, the guidewalls were analyzed in their original construction and in 1994 conditions. Analysis of the embedment of the sheet pile in its 1994 condition is presented. This example demonstrates reliability assessment and the associated output used as input into the economic risk-based model and is not intended as a complete assessment of the guidewalls, which is given the USAE Galveston District Major Rehabilitation report [4]. Table 1 presents the parameters used in the reliability analysis for the guidewall. The moist unit weight, γ , and internal friction angle, ϕ , of each soil layer is known to be correlated. Also correlated is the wall friction, δ , of the two soil layers.

Computer spreadsheets such as the one given in Table 2 were used to compute reliability indices using the appropriate statistical parameters and correlations. FS calculation for each combination of random variables was generated using the Corps' computer program CWALSHT, X0031 [1]. CWALSHT analyzes sheet pile

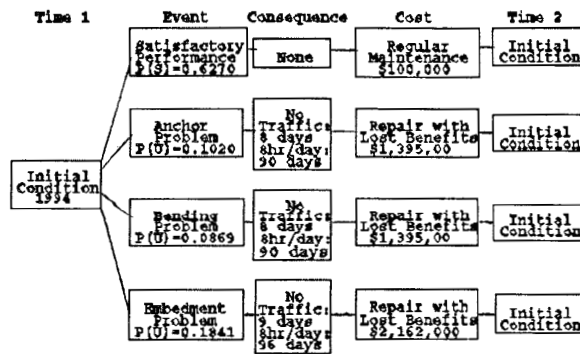


Figure 6. Single Time Period Event Tree

TABLE 1. Sheet Pile Guidewall Parameters

Random Variable		Mean	Std. Dev.
γ_{fill} (pcf)	Moist unit wt. of fill	110.0	7.0
ϕ_{fill} (°)	Internal friction angle of fill	28.0	3.0
δ_{fill} (°)	Wall friction of fill	14.0	3.0
γ_{found} (pcf)	Moist unit wt. of foundation	129.0	4.0
ϕ_{found} (°)	Internal friction angle of foundation	27.5	3.5
δ_{found} (°)	Wall friction of	13.75	3.25
Sat. (ft)	Saturation level	1.0	1.0
El _{scour} (ft)	Scour elevation	-20.0	2.0
Constant		Value	
E (psi)	Wall modulus of elasticity	29.0E+07	
I (in ⁴)	Wall moment of inertia	156	
Water (pcf)	Unit wt. of seawater	64	

walls by use of the free earth method. The reliability index for embedment loss at the guidewall is 0.90

$$\beta = \frac{\mu_{\ln C/D}}{\sigma_{\ln C/D}} = \frac{0.2239}{0.2481} = 0.90 \quad (5)$$

where the logarithm of the mean SR is

$$\begin{aligned} \mu_{\ln C/D} &= \ln \mu_{C/D} - \frac{\sigma_{\ln C/D}^2}{2} \\ &= \ln 1.29 - \frac{(0.2481)^2}{2} = 0.2239 \end{aligned} \quad (6)$$

and the logarithm of the safety ratio's standard deviation is

$$\begin{aligned} \sigma_{\ln C/D} &= \sqrt{\ln \left[1 + \left(\sigma_{C/D} / \mu_{C/D} \right)^2 \right]} \\ &= \sqrt{\ln \left[1 + (0.325 / 1.29)^2 \right]} = 0.2481 \end{aligned} \quad (7)$$

TABLE 2. Embedment of Guidewall

γ_{fill}	ϕ_{fill}	γ_{found}	ϕ_{found}	Sat.	δ_{fill}	δ_{found}	El _{scour}	CWALSHT FS C/D
117	31	129	27.5	1	14	13.75	-20	1.34
103	25	129	27.5	1	14	13.75	-20	1.25
110	28	133	31	1	14	13.75	-20	1.52
110	28	125	24	1	14	13.75	-20	1.08
110	28	129	27.5	2	14	13.75	-20	1.32
110	28	129	27.5	0	14	13.75	-20	1.26
110	28	129	27.5	1	17	17	-20	1.38
110	28	129	27.5	1	11	10.5	-20	1.20
110	28	129	27.5	1	14	13.75	-18	1.52
110	28	129	27.5	1	14	13.75	-22	1.09
C/D-SD								
0.045		0.22		0.03	0.09		0.215	
MEAN VALUES								MEAN C/D
110	28	129	27.5	1	14	13.75	-20	1.29

Standard deviation, $\sigma_{C/D}$, of the SR's probability distribution is derived from the standard deviations of the random variables. These derivatives (C/D-SD) are approximated by a finite difference expression in the Taylor series method.

A reliability index of 0.90 for embedment loss at the sheet pile guidewall indicates an unsatisfactory level of performance for this limit state. Scour has produced the loss of embedment, which has a probability of unsatisfactory performance of 0.1841. The expected consequence of this level of performance is that an emergency act will be required to alleviate a hazard caused by the loss of embedment of the piling. This amount of scour was probably not anticipated in the original design. Similarly, a reliability index of 3.47 can be calculated for the embedment loss at the time of construction, which reflects a good probability of satisfactory performance. The reliability difference for the loss of embedment at the guidewall at the time of construction (3.47) and in 1994 (0.90) is a good indicator that the reliability of the guidewalls has diminished to unacceptable levels of service due to deterioration.

Risk Model

The segment of the GIWW in which the Floodgates are located links Texas with the rest of the National inland waterway system. Typically over 16 million tons move through this reach of the GIWW each year, with liquid petrochemical constituting approximately ninety percent of this tonnage. Also, many smaller vessels pass through the Floodgates when transiting the sheltered waters of the GIWW. Therefore, the benefits for this segment of the GIWW are based on the difference in transportation costs between what the waterway users now incur and what their transportation costs would be in the event of closure of this segment of the GIWW. Alternative modes of transportation include rail and ocean-going barge. When sufficient tonnage is moved between deep-draft ports, movement is assumed to be by ocean-going barge; otherwise, movement is assumed to be by rail.

An unsatisfactory performance event at any one of the four guidewalls would temporarily close the GIWW to all barge traffic. To restore the viability of the

navigation channel, an emergency contract would be awarded so that traffic could resume on a limited scale. Repair work would begin eight to nine days after the unsatisfactory performance event, after the channel had been cleared and the backlogged traffic relieved. Emergency repair would be scheduled in 2 8-hr shifts separated by a 4-hr period for navigational use of the channel. Therefore, the savings in costs include complete tow stoppages of up to nine days and slowdowns associated with repair work in the event of failure at any guidewall.

Risk model uses input of benefits and costs along with associated probabilities of unsatisfactory performance. Reliability indices calculated from the reliability-based engineering analysis are converted into probabilities of unsatisfactory performance. For the anchored sheet pile guidewall, these probabilities, costs, and benefits are given in Table 3. These values are directly input into a simulation event tree. The single time period event tree, as in Figure 6, is extrapolated to encompass the proposed lifetime extension period for the guidewall. Through Monte Carlo simulation techniques using this multi-time period event tree and degradation rates for each performance mode, a benefit-cost ratio can be calculated. This ratio can then be used to determine the benefit of rehabilitating the structure at the proposed time.

Conclusion

A reliability-based engineering analysis is preferred over FS's for assessing performance levels in Corps structures. FS's relate the reserve capacity between expected loads and structural failure and do not directly relate serviceability or performance. Traditional structural analysis chooses conservative design values based on experience and judgment, whereas probabilistic analysis yields reliability indices from the average value and variability of the input variables.

The major emphasis of this ongoing study is to provide methods for assessing the condition of Corps structures by reliability-based models that are mathematically sound. This work established the basis for general criteria development [2, 3] and several supporting models to assess aging structures including time-dependent degradation in steel structures and concrete lock walls. Methods have been incorporated into an economic risk-based model which was used to justify funding for major rehabilitation at several Corps structures, including this one.

TABLE 3. Guidewall Risk Model Parameters

Performance Mode	β	P(u)	Benefits Foregone	Costs	Degrad. Rates
Loss of Embedment	0.90	0.1841	3,931,000	2,162,000	0.0000
Anchor Rod Tension	1.27	0.1020	3,267,000	1,395,000	0.0050
Bending Stresses	1.36	0.0869	3,267,000	1,395,000	0.0038

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