Loads for Fatigue Life Assessment of Gates at Navigation Locks

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Abstract: The U.S. inland navigation infrastructure is deteriorating primarily due to the aging of its components and the operation at near to full capacity of the system's structures. Gates at navigation locks play an integral part in keeping navigation traffic continuously moving, and their reliability is essential to the navigation infrastructure. Assessments of fatigue reliability as a function of time for existing gates at navigation locks require knowledge of loading cycles. This assessment can contribute to the economic evaluation of the remaining fatigue life of critical fatigue details in gates. The accuracy of this assessment depends in part on the accuracy of the loading cycles used in the reliability analysis. Water elevations from hydraulic records were used to compute water-head differentials on the miter gates. Loading or hardware cycles were obtained from the U.S. Army Corps of Engineers (USACE) lock performance monitoring system (LPMS), and were then combined with head differential to obtain loading histograms for the gates. These histograms are needed to successfully perform fatigue reliability analyses. A probabilistic model was also developed for predicting the number of loading or hardware cycles for the gates. This paper includes an example to demonstrate the suggested methods and models for fatigue reliability assessment.

INTRODUCTION AND BACKGROUND

The navigation structures of the U.S. Army Corps of Engineers (USACE) provide a vital link in the national infrastructure. Many structures are approaching their design life and/or capacity. Miter gates are one of the major infrastructure components that need to be examined. A limited amount of funding is currently available to maintain, rehabilitate, improve, or replace these aging structures. Rehabilitation funding for a project, therefore, must be justified by demonstrating a need for improvement in reliability or efficiency.

Miter gates at navigation locks experience loading cycles from the emptying and filling of a lock's chamber as they are opened and closed to allow traffic through the navigation locks. Due to the cyclic-loading nature of miter gates, the fatigue of critical details requires examination using reliability methods. Assessment of fatigue reliability of these details as a function of time requires knowledge of strength, stress ranges, and loading cycles for these details. Also, it requires determining stress concentrations and residual stresses, which can be difficult. These aspects of stress computations are beyond the scope of this paper.

The strength of fatigue details can be expressed in the form of stress-range versus number of cycles (S-N) curves. The determination of stress ranges requires analyzing miter gates under different loading conditions. The number of loading cycles also constitutes an important component in the reliability analysis, in addition to its use in determining the reliability as a function of time. The resulting reliability can form the basis for economically evaluating the remaining life of critical fatigue details in miter gates. The accuracy of this assessment depends in part on the accuracy in the used loading cycles in the reliability analysis.

The objectives of this paper are to describe the factors that affect loading cycles of structural details of miter gates at navigation locks, develop a methodology for computing the number of loading cycles with its uncertainties, discuss the use of computed loading cycles in fatigue life assessment, develop a loading-cycles histogram for miter gates, and demonstrate the methodology using an example.

The fatigue failure mode is commonly considered in detail design, after principal structural members have been sized. Several procedures have been used for the assessment of fatigue damage [e.g., Wirsching (1984); Wirsching and Chen (1987); Chen and Mavrakis (1988)]. Fatigue reliability can then be evaluated (Munse et al. 1982; Wirsching 1984; Madsen et al. 1986). A reliability-based design format for fatigue was demonstrated by White and Ayyub (1987).

Fatigue can result from the cyclic loading applied to miter gates of navigation locks as they are operated to perform lockages of vessels going through the locks. Cyclic loading on a gate is generated by the cyclic head and tailwater pressures on the gate. Therefore, variable amplitude stress ranges are applied to critical fatigue details of the gate. The reliability of fatigue details can be assessed using Miner's rule of cumulative fatigue damage under variable amplitude stress range. This model requires S-N information for the fatigue details (ASCE Committee on Fatigue and Fracture Reliability 1982; Ayyub and White 1990; Ayyub et al. 1990; Ricles and Leger 1993; Sommer et al. 1993; USACE 1994). Fatigue analysis of miter gates is described in *ETL 1110-2-346* (USACE 1993). The data needed for fatigue reliability assessment include: (1) types of fatigue details; (2) statistical description of the S-N curves for the fatigue details (Fisher et al. 1974); (3) materials and their strength and stiffness properties, such as the modulus of elasticity and Poisson's ratio; (4) structural geometry and dimensions; (5) stress concentrations and residual stresses; (6) joint histograms of loading cycles and water heads on both sides of the gate as a function of time; and (7) modeling uncertainties in Miner's rule and computed stresses.

FATIGUE LIFE ASSESSMENT

The performance function for fatigue reliability analysis expresses the relationship between the strength and load effects for a detail in a structural member. It can be expressed as the number of loading cycles to fatigue initiation minus the num-

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ber of loading cycles expected from start of service to some time (such as the present). The performance function is used as a basis for computing the fatigue-initiation probability. It can be evaluated using reliability assessment methods, such as the advanced second moment method (Ayyub and White 1990, 1995).

The strength (or resistance) of a structural component and the load effects are generally functions of time. Therefore, the probability of fatigue initiation is also a function of time. The time effect can be incorporated in the reliability assessment by considering the time dependence of both the strength and load effects. Time dependence of structural reliability is due to the variations over time of load effects and strength, and each are modeled differently. The time dependence of load effects can be modeled using one of the following three approaches: (1) stochastic process modeling; (2) extreme value modeling; and (3) cumulative value modeling. The selection of the appropriate model depends on the nature of the load effect. In stochastic process modeling, the load effect is modeled as a stochastic process in which the instantaneous value of the load at a point in time is defined. Therefore, the time duration aspect is not present in the modeling process. In the extreme value modeling, the statistical characteristics of the extreme load in a time period can be determined using extreme value statistics. The resulting extreme value probability distribution can be used to determine the reliability. By varying the time period from zero to a designed structural period, a plot of reliability as a function of time can be developed. This method can be used in reliability and structural life assessment according to certain performance modes, e.g., plastic deformation and buckling. For other performance modes, e.g., fatigue, the failure event occurs because of the accumulation of damage due to repeated application of cyclic loads of variable amplitudes with varying frequencies. According to cumulative value modeling, the variable amplitude and frequency loading that causes fatigue initiation can be transformed into an equivalent constant amplitude loading necessary to cause fatigue initiation. The number of load cycles to fatigue initiation can be related to the number of years of structural service. Therefore, the cumulative value loading and resulting probability of fatigue initiation are a function of the number of load applications, which means that they are a function of time. The strength (or resistance) of a structure is also a function of time. Generally, most steel structural members become weaker over the course of time due to material corrosion and deterioration.

Based on time-dependent loading cycles and strengths, the time-dependent probability of fatigue initiation can be computed. Mathematically, the probability of fatigue initiation can vary from zero to one during the life of a structure. Realistically, the reliability varies from an initial (design) level based on design values to a final level at the end of the design life. The resulting variation of the probability of fatigue initiation with time can be viewed as the cumulative distribution function of the fatigue life. This curve satisfies all the conditions of a cumulative probability distributon function. The probability density function of fatigue life can then be interpreted, based on the basic definition of density functions, as the unconditional probability of fatigue initiation per unit time, or the unconditional instantaneous probability of fatigue initiation, or the unconditional fatigue-initiation rate. In contrast, a conditional probability of fatigue initiation per unit time can be defined. If conditioning is performed on the event (structural survival in a time period from start of life to present), the resulting conditional probability of fatigue initiation is called the hazard function. The hazard function measures the probability of fatigue initiation per unit time given that a structural detail did not have fatigue initiation in the time interval (0, present). Therefore, the hazard function plot with time shows the change in this probability of fatigue initiation as the structural component becomes older. The mean value, variance, and confidence levels of fatigue life can be determined. The mathematical formulation of this approach was developed and used for service fatigue life assessment of patrol boats by Ayyub and White (1990, 1995).

FATIGUE LOADING CYCLES FOR MITER GATES

Factors Affecting Loading Cycles

The number of loading cycles for miter gates is a random variable with inherent uncertainty resulting from sources that include: (1) navigation traffic volume; (2) traffic composition primarily in terms of tow length; (3) length and capacity of navigation locks; (4) traffic direction and pattern; (5) weather-related conditions, e.g., ice buildup and debris; and (6) impact loads. Impact loads were not modeled in the present paper, although they can contribute to the fatigue degradation of gates.

The USACE lock performance monitoring system (LPMS, USACE 1990) includes information such as lock number, lockage date, start of lockage, direction of lockage, number of cuts, number of vessels in a lockage, vessel type, entry type, exit type, end of lockage, and tonnage. These are selected fields of the LPMS from about 50 fields. LPMS entries can be used to compute loading cycles needed for fatigue-reliability evaluation. However, computation of these cycles from the LPMS can require a significant level of effort due to the structure of LPMS.

Hydraulic-operation records include pool and tailwater elevations that can be obtained on a daily basis. The pool elevation (or height) of water (H_p) and the tail elevation (or height) of water (H_t) are needed on a daily basis from the start of the LPMS (i.e., January 1980) to the present. H_p and H_t can be used to compute stresses and stress ranges at critical fatigue locations, whereas the number of repetitions of the pairs (H_p, H_t) produces the needed frequency of the corresponding stress ranges. Therefore, stress-range frequency histograms necessary for fatigue analysis can be produced. The number of repetitions of the pairs (H_p, H_t) can be computed from data in the LPMS. The number of loading cycles for miter gates is considered in this study to be a random variable.

Stages for Computing Loading Cycles

The economic life of the gate can be viewed to consist of its present age plus the planned remaining design life. Estimates of loading cycles up to the present can be determined using methods that depend on the type of available information. Estimates of future loading cycles need to be based on forecasting models of future traffic in a navigation system.

In this section the terms lockage, lockage cut, hydrostatic loading cycles, and hardware cycles are used. In general, a lockage is defined as a series of events required to transfer a tow or vessel with all its barges through a lock in a single direction. For the purpose of this paper, a lockage cut is defined as a process of passing one cut of a tow of several vessels together through a lock. This process requires the operation of the gates of the lock (the emptying or filling of a lock's chamber) once, if the gates are favorably positioned to an inbound cut of a vessel. If a vessel can be accommodated in the lock in its entirety, then only one emptying and one filling of the lock's chamber are required. Also, if several vessels can be simultaneously accommodated in the lock, then one emptying and one filling of the lock's chamber are required. However, if a vessel is too large to be accommodated in the lock, it is separated into two or more cuts. Several lockage cuts in this case are required to pass through all the cuts by emptying and filling the lock's chamber several times. The number of lockage cuts in this case is equal to the number of cuts passed in the lock. If a lock's state is not in a favorable position to receive an inbound vessel, an additional cycle of emptying or filling of the chamber is required. A hydrostatic loading cycle consists of a complete emptying and filling of a lock's chamber that produces a hydrostatic water-head differential on the gates. A hardware cycle is a complete emptying or filling of a lock's chamber that produces hydrostatic water-head differential on the gates. Therefore, a hydrostatic loading cycle consists of two hardware cycles.

LPMS generally covers the period 1980 to present. The time period before 1980 can be broken down into several stages depending on the available information. For example, it can be broken down into two stages, start of gate life (completion of construction, e.g., around late 1930s and early 1940s for some locks on the Mississippi River) to 1948, and 1948–80. It seems that formal traffic record keeping for these locks was not established until the late 1940s. Therefore, the following stages can be identified for developing methods for estimating loading cycles: (1) start of life of a gate (e.g., 1940) to 1948; (2) 1948 to start of the LPMS (i.e., 1980); (3) start of LPMS (1980) to present; and (4) present to planned design (or rehabilitation) life. In this section methods for assessing loading cycles for these stages were developed. Stage 3 (i.e., the LPMS stage) contains information with the highest levels of data quality and certainty. Therefore, this stage can be used as a basis for estimating some of the parameters in other stages.

The first stage was defined as the stage from the start of life of a gate to about 1948. Generally, the information available from records in this stage is limited to annual tonnage, changes in tows, and number of individual barges. Therefore, the relationships of hardware cycles or lockage cuts as functions of tonnage that were developed in the LPMS (third) stage can be used to estimate hardware cycles and lockage cuts, respectively, for this stage. Also, tow changes over time should be considered in this estimation process. The second stage is defined as the stage from about 1948 to the start of the LPMS stage. Generally, the information available from records in this stage is limited to annual lockages and annual tonnage. Therefore, similar prediction methods as for the first stage can be used. The fourth stage begins with the present and continues to the planned end of design (or rehabilitation) life of a gate. The models in this stage can be based on forecasting techniques. This paper does not include the development of forecasting models. However, forecasts of annual tonnage as a function of time based on a set of input variables, and the relationships of hardware cycles and lockage cuts as functions of tonnage that were developed in the LPMS (third) stage can be used to estimate hardware cycles and lockage cuts, respectively, for this stage.

In the third stage or LPMS stage, the following quantities are of interest: (1) pool elevation (or height) of water (H_p); (2) tail elevation (or height) of water (H_t); and (3) the corresponding number of repetitions of the pair (H_p, H_t). Due to the observed daily variability in the water elevations, these quantities need to be computed on a daily basis from January 1980 to present. A special logic was developed for computing hardware cycles on a daily basis from the LPMS fields (Ayyub et al. 1995). The logic accounts for the additional hydrostatic loading cycles needed to position the gates in a favorable position for receiving incoming vessels to the lock. This effect was accounted for by considering the sequences for the direction of traffic. The data reduction and analysis of the hydraulic records and the LPMS fields produce daily quantities for pool water elevation (H_p), tailwater elevation (H_t), number of hardware cycles, and number of lockage cuts. These results can be used to compute the loading cycles of interest using the following steps:

1. Develop a relationship between pool water elevation and tailwater elevation.
2. Sum the numbers of hardware cycles for intervals of tailwater elevations. A histogram of tailwater elevation and fraction of total cycles can then be developed.
3. Fit a probability density function to the histogram resulting from step 2.
4. Determine the total numbers of hardware cycles and lockage cuts on monthly and yearly bases from the daily records.
5. Establish monthly or annual relationships between hardware cycles and lockage cuts, hardware cycles and tonnage, hardware cycles and time, lockage cuts and time, and tonnage and time. These relationships are needed in other stages.

The models that result from steps 3 and 5 constitute the basis for assessing the loading cycles. These models can be expressed in dimensionless format by normalizing with respect to corresponding design values. The benefit of expressing the results in a normalized format is in potentially increasing the range of applicability of the results to other locks. In general, locks and dams along a river can be classified into groups (or reaches). A typical lock can be analyzed from each reach, and several locks in a selected reach can be analyzed to produce a complete understanding of loading cycles on miter gates. Future work in this area can examine the relationships and variability among the reaches and within reaches.

Probabilistic Model for Loading Cycles

The objective of the model proposed in this section is to predict the number of hardware cycles on miter gates as a function of either the number of vessels passing through a lock or the number of lockage cuts that occur at a lock. The model accounts for the following factors: (1) navigation traffic volume; (2) traffic composition in terms of vessels lengths; (3) length and capacity of navigation locks; (4) traffic pattern (in terms of upstream/downstream ratio); and (5) environmental conditions (loading cycles connected with passing ice and debris). The development of the relationship between the number of hardware cycles and the number of vessels (or traffic volume) is divided into the following four cases: (1) the increase in the number of hardware cycles due to cutting of long vessels, assuming the traffic is in one direction; (2) the effect of simultaneous lockages of light boats or recreational vessels; (3) the decrease in the number of hardware cycles due to travel in opposite (upstream and downstream) directions; and (4) the effect of environmental conditions (debris and ice lockages). These four cases are discussed in this section.

Case 1—Increase in Number of Hardware Cycles due to Cutting of Long Vessels

The maximum length (l_{max}) of a vessel that can be locked in one operation of a lock and the cumulative distribution function of length of the vessel population [$F_L(l)$] determine the number of needed cuts. The length of the vessel population is a discrete random variable with the following cumulative distribution function:

$$F_L(l) = \sum_{l_i \le l} p_L(l), \quad \text{for } i = 1, 2, \ldots, NL \qquad (1)$$

where $p_L(l_i)$ = probability mass value for a vessel of a length l_i for NL possible discrete vessel lengths. The arrival of vessels in one direction at a lock can be assumed to follow a Poisson distribution with a rate λ. For a time period of interest (T), which is nonrandom, the mean number of vessels that arrives at the lock during the time T is

$$\bar{N}_v = \lambda T \tag{2}$$

where $\bar{N}_v$ = mean number of vessels arriving in time T. The probability (P_1) that a vessel is not cut into two or more parts is given by

$$P_1 = F_L(l_{max}) \tag{3}$$

The probability (P_2) that a vessel is cut into two parts is given by

$$P_2 = F_L(2l_{max}) - F_L(l_{max}) \tag{4}$$

Analogously, the probability (P_k) that the vessel is cut into k parts is given by

$$P_k = F_L(kl_{max}) - F_L[(k-1)l_{max}] \tag{5}$$

where k = number of parts into which vessels can be cut. In general, the probability that for a given number of vessels N_v, exactly N_1 vessels will not be cut, N_2 will be cut into two parts, and so on, is given by the multinomial distribution with parameters N_v, P_1, P_2, . . . , P_k. The probabilities P_1, P_2, . . . , P_k should add up to 1 as follows:

$$\sum_{i=1}^{k} P_i = 1 \tag{6}$$

If N_v (the number of vessels that arrive at a lock in one direction during reference time period T) is treated as a nonrandom variable, the number of vessels with one or more parts (i = 1, 2, . . . , k parts) due to cutting has the following mean ($\bar{N}_i$) and variance [Var(N_i)], respectively:

$$\bar{N}_i = N_v P_i \tag{7a}$$

$$\mathrm{Var}(N_i) = N_v P_i (1 - P_i) \tag{7b}$$

For an incoming vessel to a lock with its gates in a favorable position (i.e., a fly entry with lock-chamber pool at incoming elevation) that needs to be cut into i parts, the number of hardware cycles ($\bar{N}_{HCi}$) is related to N_v and P_i as

$$\bar{N}_{HCi} = (2i - 1)N_v P_i, \quad \text{for } i = 1, 2, \ldots, k \tag{8}$$

Therefore, the mean of the total number of hardware cycles ($\bar{N}_{HC}$) can be related to the number of vessels as

$$\bar{N}_{HC} = N_v \sum_{i=1}^{k} (2i - 1)P_i \tag{9}$$

The variance of the total number of hardware cycles can be written as

$$\mathrm{Var}(N_{HC}) = N_v^2 \sum_{i=1}^{k} (2i - 1)^2 P_i (1 - P_i) \tag{10}$$

Case 2—Effect of Simultaneous Lockages of Light Boats or Recreational Vessels

It is common in operating locks to simultaneously service a number of small vessels in the same lockage, as is the case for light or receational boats. The effect of this practice on hardware cycles is a reduction in its total number. Therefore, the preceding approach can be generalized to take this decrease into account. Let p_s be the probability that a given boat is being serviced simultaneously with other boats, then the mean total number of hardware cycles should be decreased by the value ΔN_{HC}

$$\Delta N_{HC} = 2N_v p_s \tag{11}$$

The combination of (9) and (11) produces

$$\bar{N}_{HC} = N_v \left(\sum_{i=1}^{k} (2i - 1)P_i - 2p_s \right) \tag{12}$$

In this case, the following condition needs to hold:

$$\sum_{i=1}^{k} P_i + p_s = 1 \tag{13}$$

The mean of the total number of hardware cycles according to (12) is a linear function of the number of vessels for traffic in one direction. For cases where $\bar{N}_{HC} > N_v$, the increase in the number of hardware cycles due to the cutting of long vessels prevails over the decrease in the number of hardware cycles due to simultaneous lockages of small vessels, and vice versa.

In the LPMS, the number of lockage cuts (N_{loc}) for vessels is defined as

$$N_{loc} = N_{cuts} \tag{14}$$

With N_{cuts} = number of cuts, (14) can be rewritten using (7*a*) as

$$N_{loc} = N_v \sum_{i=1}^{k} iP_i \tag{15}$$

where N_{cuts} takes the values of 1, 2, 3, . . . , k in which 1 corresponds to a vessel without a cut. In this case (12) becomes

$$\bar{N}_{HC} = (2N_{loc} - N_v) - 2N_v p_s \tag{16}$$

Eq. (16) can be rewritten using (15) to produce the following relationship between mean total hardware cycles and number of lockage cuts:

$$\bar{N}_{HC} = (2N_{loc} - N_v) - 2p_s \frac{N_{loc}}{\sum_{i=1}^{k} iP_i} \tag{17}$$

Case 3—Decrease in Number of Hardware Cycles due to Travel in Opposite (Upstream and Downstream) Directions

To model the effect of two-direction traffic on hardware cycles, let λ_u and λ_d be the Poisson rates of traffic moving in upstream and downstream directions, respectively, and N_{vd} and N_{vu} be the overall number of vessels arriving at a lock from a downstream and upstream directions during the reference period T. If δt_d is the service time in the lock for a vessel in the downstream traffic, the mean decrease in the number of hardware cycles (ΔN_{HCd}) for steady-state traffic is

$$\Delta N_{HCd} = N_{vd} \lambda_{up} \delta t_d \tag{18}$$

Since $N_{vd} + N_{vu} = N_v$, the downstream number of vessels $N_{vd} = N_v(1 - \alpha)$, where $0 \le \alpha \le 1$, $N_{vu} = \alpha N_v$, and α = fraction of traffic moving upstream. Using the estimate $\lambda_u = N_{vu}/T$, (18) can be expressed as

$$\Delta N_{HCd} = \frac{\alpha(1 - \alpha)N_v^2 2\delta t_d}{T} \tag{19}$$

Analogously, the mean decrease in the number of hardware cycles due to the traffic in the opposite (upstream) direction is

$$\Delta N_{HCu} = \frac{\alpha(1 - \alpha)N_v^2 2\delta t_u}{T} \tag{20}$$

where δt_u = service time in the lock for a vessel in the upstream traffic; and ΔN_{HCu} = mean decrease in the number of hardware cycles in the upstream traffic. The sum of (19) and (20) is the total decrease in the number of hardware cycles (ΔN_{HCt}), which can be expressed as

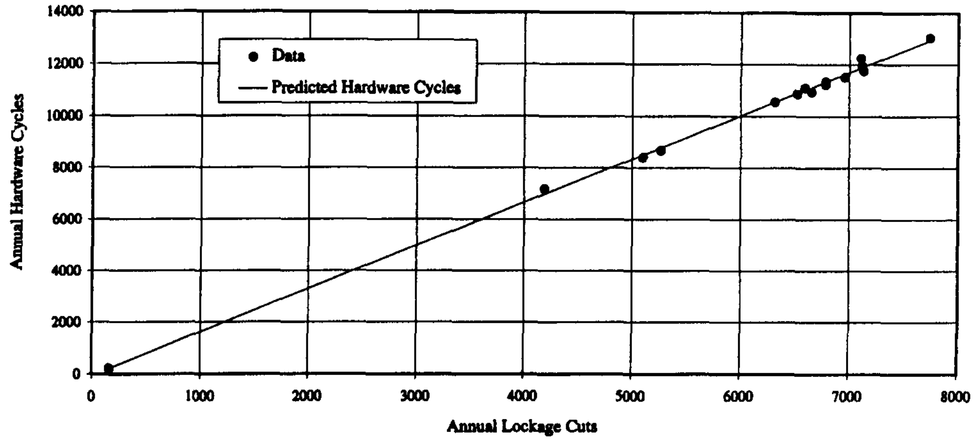


FIG. 1. Annual Lockage Cuts and Hardware Cycles

$$\Delta N_{HCt} = \frac{\alpha(1 - \alpha)N_v^2 2\delta t}{T} \qquad (21)$$

where $\delta t = (\delta t_u + \delta t_d)/2$. A strong seasonal variation in the number of vessels can result in considerable variation of α. Thus, in this case the number of vessels passing through the lock cannot be considered to be a Poisson process. Under this restriction (2) needs to be used as follows: (1) the reference time period in this case can be taken as a month, i.e., T_i where $i = 1, 2, \ldots, 12$; (2) the fraction of upstream traffic is α_i, which is related to the ith month; and (3) and number of vessels in the ith month is N_{vi}, so that if N_v is the annual number of vessels, then

$$N_{vi} = \beta_i N_v \qquad (22)$$

where β_i = fraction of vessels in the ith month from the traffic of a year such that $\Sigma_{i=1}^{12} \beta_i$. Thus, in this case (21) takes on the following form:

$$\Delta N_{HCt} = \frac{2\delta t N_v^2}{T} K \qquad (23)$$

where $K = \Sigma_{i=1}^{12} \alpha_i(1 - \alpha_i)\beta_i^2$ = coefficient for expressing seasonal variation in traffic volume and direction.

Case 4—Effect of Environmental Conditions

Some of the hardware cycles for miter gates can be attributed to environmental conditions such as river debris and ice passing in the winter. If these lockages were recorded in the LPMS as real lockages with the appropriate numbers of hardware cycles, they could be easily taken into account by the model by adding a term to (12). Since these lockages are currently not recorded in the LPMS, their hardware cycles can be taken into account by adding a positive constant term in any developed regression model to fit real data for the number of hardware cycles and the annual tonnage as previously described.

A regression model can be developed as the relationship between hardware cycles and lockages cuts using real data, e.g., based on the LPMS. Eqs. (12) and (21) can be combined to obtain the following model for monthly data with a constant term (C) that corresponds to the hardware cycles associated with the environmental conditions:

$$\bar{N}_{HC} = N_v \left[\sum_{i=1}^{k} (2i - 1)P_i - 2p_s \right] - \frac{\alpha(1 - \alpha)N_v^2 2\delta t}{T} + C \qquad (24)$$

The mean hardware cycles according to (24) can be expressed in terms of N_{loc} instead of N_v based on (15) and (17) as

$$\bar{N}_{HC} = (2N_{loc} - N_v) - 2p_s \frac{N_{loc}}{\sum_{i=1}^{k} iP_i} - \frac{\alpha(1 - \alpha)2\delta t}{T} \frac{N_{loc}^2}{\left(\sum_{i=1}^{k} iP_i\right)^2} + C \qquad (25)$$

which is a quadratic equation in terms of N_{loc}, i.e.

$$\bar{N}_{HC} = AN_{loc} - BN_{loc}^2 + C \qquad (26)$$

where A, B, and C = model coefficients with $B \geq 0$. Fig. 1 shows a scatter diagram of annual lockage cuts and hardware cycles using the annual data for an example (typical) lock that is used in the example section. The scatter diagram shows a linear relationship between hardware cycles and lockage cuts, i.e., $B = 0$ in (26). For the case $B = 0$ and $C = 0$, coefficient A has the same meaning as K_c used in Padula et al. (1994), i.e., the mean hardware cycles per lockage cut. An estimate of the correlation coefficient for the linear model was found to be 0.999. The estimates of the coefficients of (26) and their corresponding standard errors are given by

$$\hat{A} = 1.67898 \pm 0.0213 \qquad (27a)$$

$$\hat{B} = 0 \text{ (not significant)} \qquad (27b)$$

$$\hat{C} = -55.1587 \pm 134.07 \text{ (not significant)} \qquad (27c)$$

Based on the data used in this analysis, only the coefficient A is significant and should be kept in the model. The developed model is of an adequate precision level for all practical purposes since the standard error of estimates is 148.85 for a sample size of 15 annual values. The results and observations provided herein are lock-specific. For data obtained from other locks, with different patterns of traffic, the significance of coefficients A, B, and C can be different.

EXAMPLE

This section demonstrates the use of the described methodology for assessing the number of hardware cycles for a vertical beam of miter gates at a navigation lock. This example concentrates on determining from actual field data the calculation of a loading histogram that would be used in a fatigue life assessment. The snapshot estimation of the reliability or safety index is examined to compare the benefits of using the more rigorous load histogram approach.

The daily hydraulic records were obtained for a navigation lock for the period 1975–94. Figs. 2 and 3 show these variations for the pool and tailwater elevations showing their daily

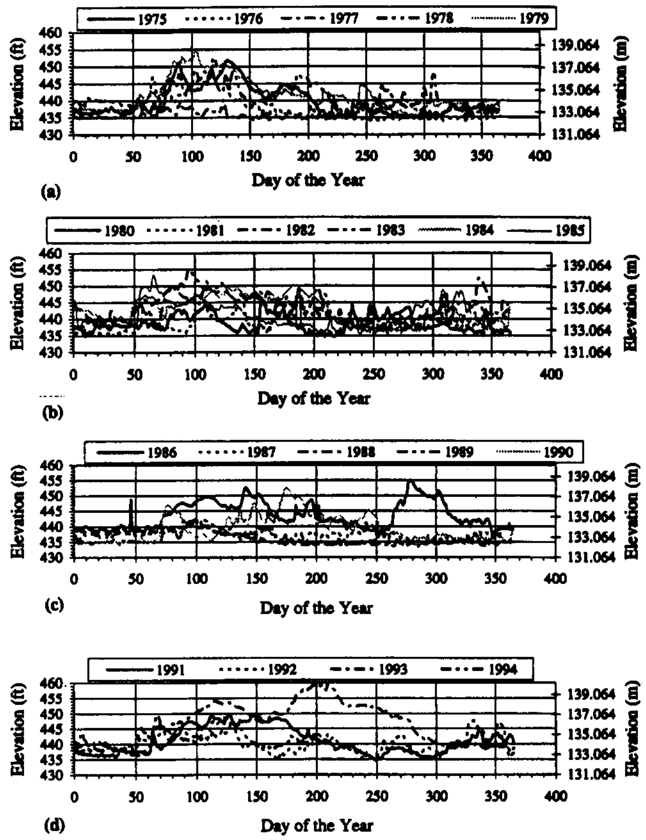


FIG. 2. Tailwater Elevation

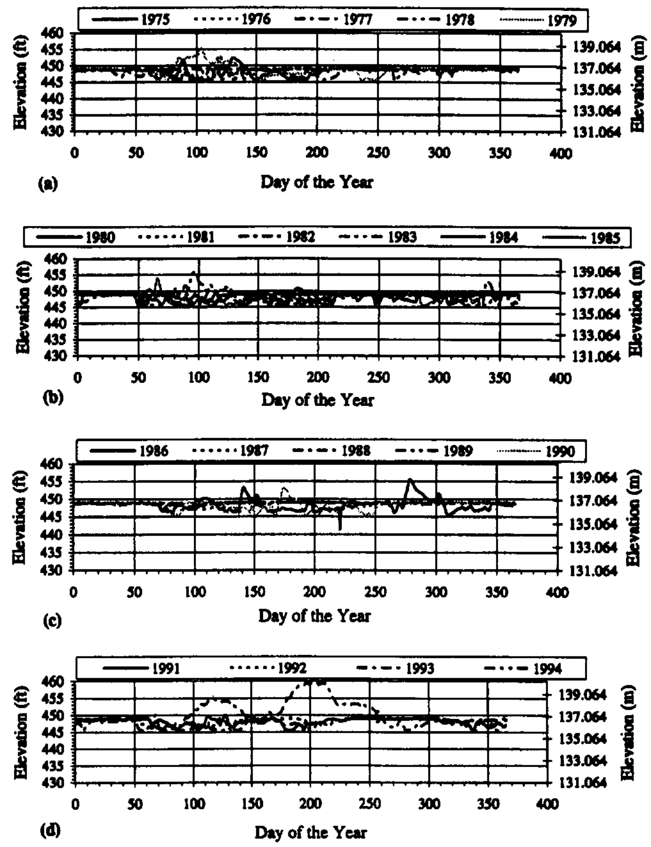


FIG. 3. Pool Water Elevation

variability, respectively. In operating a lock and dam, a lockmaster maintains the pool water level by adjusting the dam's gates. However, several factors contribute in the variability to the pool water elevation, e.g., increased flow levels into the river and actions by the lockmaster of upstream and downstream locks to control their own pool water levels. Therefore, pool and tailwater elevations are expected to be highly correlated. The pool water elevation for the lock was plotted as a function of the tailwater elevation in Fig. 4. From this figure the following three regions were identified: (1) low tailwater elevation, $H_t < 133.807$ m (439 ft); (2) medium tailwater elevation, 133.807 m (439 ft) $\leq H_t < 135.655$ m (445.062 ft); and (3) high tailwater elevation, $H_t \geq 135.655$ m (445.062 ft). These regions were separately analyzed.

The first region can be characterized with a high level of control in maintaining the pool water elevation by the lockmaster. The pool water elevation in this region is maintained at a constant level regardless of the tailwater elevation. Correlation analysis of pool and tailwater elevations shows that the correlation level is not significant. Using the daily hydraulic record, the statistical characteristics of the pool water elevation in this region were computed. The mean pool water elevation was estimated to be 136.822 m (448.89 ft), and the standard deviation was 0.0792 m (0.26 ft). The sample size for this region was 3,579, which gives a standard error for the mean of 0.00134 m (0.0044 ft) as given in (28). The maximum and minimum pool water elevations were 137.154 m (449.98 ft) and 135.810 m (445.57 ft), respectively. The resulting model is shown in Fig. 4. The region of medium tailwater elevation shows some correlation with pool water elevation as shown in Fig. 4. Therefore, linear regression analysis was performed, resulting in a correlation coefficient of −0.858. A linear prediction model of pool water elevation was developed for this region. Each coefficient in the model was developed with its standard error. The standard error of estimates for the model was 0.561 based on a sample size in this region of 2,356. Both the slope and the intercept are statistically significant as given in (28). The region of high tailwater elevation shows strong correlation with pool water elevation as shown in Fig. 4. Therefore, linear regression analysis was performed, resulting in a correlation coefficient of 0.996. A linear prediction model with a slope coefficient and zero intercept was computed as shown in (28). The standard error of estimates for the model was 0.238 based on a sample size in this region of 1,207. The resulting model is shown in Fig. 4 that can be expressed as

$$\hat{H}_p = \begin{cases} 448.89 \pm 0.0044, & H_t < 439 \text{ ft} \\ (-0.5531396 \pm 0.0068267)H_t & 439 \leq H_t < 445.062 \text{ ft} \\ \quad + (691.72094 \pm 3.01333), & \\ (1.00118 \pm 0.00001525H_t, & H_t \geq 445.062 \text{ ft} \end{cases} \tag{28}$$

where $\hat{H}_p$ = predicted value of H_p. The design pool and tailwater elevations were 136.855 (449.0) and 133.685 m (438.6 ft), respectively. Eq. (28) can be normalized with respect to the design pool elevation [136.855 m (449 ft)] and tailwater elevation [133.685 m (438.6 ft)] to obtain the normalized pool water elevation (H_{pn}) as a function of the normalized tailwater elevation (H_{tn}) as follows:

$$H_{pn} = \begin{cases} 0.999755 \pm 0.0000097, & H_{tn} < 1.000912 \\ (-0.5403274 \pm 0.0066685)H_{tn} & 1.000912 \leq H_{tn} \\ \quad + (1.5405812 \pm 0.0067112), & \quad < 1.0147332 \\ (0.97799 \pm 0.0000148)H_{tn}, & H_{tn} \geq 1.0147332 \end{cases} \tag{29}$$

The daily hardware cycles were computed based on the LPMS and adjusted for ice hardware cycles. The adjustment for the ice lockages was based on time-lapsed videotapes in the winter months of 1993–94 for two locks on the Mississippi River (Patev 1995). The videotapes showed 63 and 75 ice lockages, respectively, over periods of 77 and 65 d of frozen river conditions, respectively. Therefore, one ice lockage per day was assumed and added to the computed lockage cuts

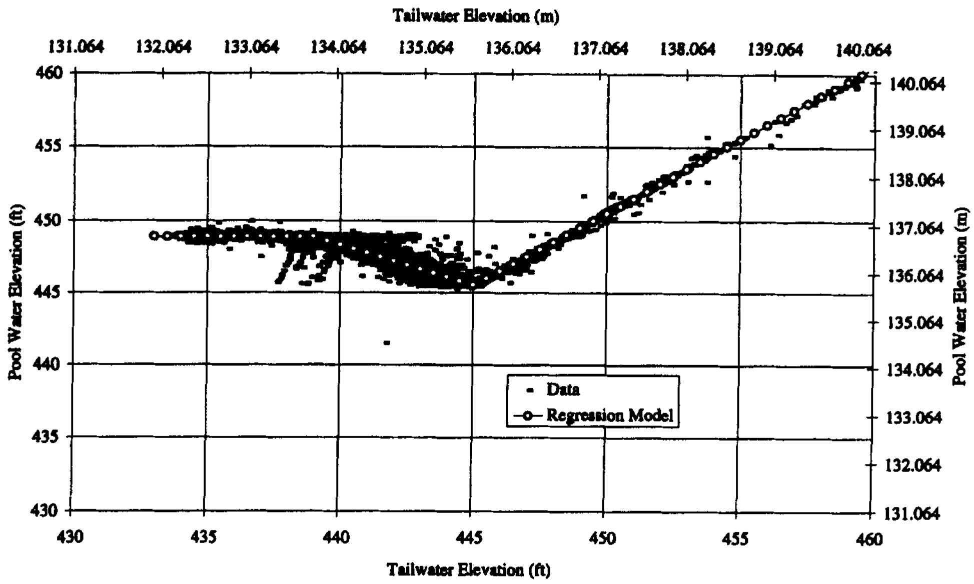


FIG. 4. Water Elevations 1975–94

TABLE 1. Summary of Lockage Cuts 1980–94

Month (1)	Year														
	1980 (2)	1981 (3)	1982 (4)	1983 (5)	1984 (6)	1985 (7)	1986 (8)	1987 (9)	1988 (10)	1989 (11)	1990 (12)	1991 (13)	1992 (14)	1993 (15)	1994 (16)
January	124	117	120	164	110	90	114	104	90	57	136	106	—	132	68
February	84	102	81	138	286	71	88	99	92	51	234	123	34	105	94
March	346	566	419	481	608	433	374	447	560	452	685	555	710	466	—
April	606	706	651	493	790	589	483	604	761	726	772	740	777	390	—
May	602	723	810	695	690	541	515	743	840	789	878	754	836	627	—
June	673	697	718	745	630	501	554	682	710	803	806	743	814	657	—
July	766	667	669	847	638	614	577	797	766	871	954	899	977	—	—
August	859	803	785	833	691	559	676	838	823	732	886	857	893	241	—
September	841	698	643	819	613	532	583	709	771	707	752	691	709	674	—
October	765	625	497	810	604	448	426	700	776	704	689	693	566	654	—
November	685	699	602	793	686	523	648	568	683	690	676	642	538	—	—
December	304	385	324	290	249	198	224	232	259	205	275	160	263	243	—
[Total]	[6,655]	[6,788]	[6,319]	[7,108]	[6,595]	[5,099]	[5,262]	[6,523]	[7,131]	[6,787]	[7,743]	[6,963]	[7,117]	[4,189]	[162]

Note: One ice lockage per day during January and February was added for all years.

TABLE 2. Summary of Hardware Cycles 1980–94

Month (1)	Year														
	1980 (2)	1981 (3)	1982 (4)	1983 (5)	1984 (6)	1985 (7)	1986 (8)	1987 (9)	1988 (10)	1989 (11)	1990 (12)	1991 (13)	1992 (14)	1993 (15)	1994 (16)
January	179	161	165	234	133	109	146	145	128	63	191	133	—	189	88
February	96	153	97	201	464	86	116	139	124	54	351	172	9	146	128
March	585	968	711	835	1,052	740	633	776	970	788	1,181	970	1,236	811	—
April	1,023	1,217	1,122	893	1,346	1,008	830	1,015	1,293	1,223	1,335	1,276	1,347	675	—
May	1,003	1,220	1,347	1,191	1,180	901	882	1,251	1,405	1,309	1,545	1,264	1,420	1,122	—
June	1,115	1,157	1,222	1,252	1,057	839	899	1,124	1,175	1,330	1,415	1,233	1,383	1,120	—
July	1,250	1,113	1,100	1,429	1,075	976	936	1,302	1,220	1,410	1,589	1,438	1,632	—	—
August	1,379	1,328	1,315	1,495	1,164	928	1,078	1,404	1,323	1,207	1,447	1,352	1,486	421	—
September	1,387	1,155	1,064	1,461	1,013	872	930	1,181	1,261	1,175	1,201	1,146	1,128	1,166	—
October	1,257	1,046	844	1,413	1,026	746	758	1,169	1,287	1,165	1,176	1,134	937	1,110	—
November	1,158	1,175	1,015	1,354	1,173	886	1,100	970	1,142	1,171	1,155	1,126	918	—	—
December	511	647	552	481	419	319	368	389	431	341	466	276	443	410	—
[Total]	[10,943]	[11,340]	[10,554]	[12,239]	[11,102]	[8,410]	[8,676]	[10,865]	[11,759]	[11,236]	[13,052]	[11,520]	[11,939]	[7,170]	[216]

Note: One ice cycle per day during January and February was added for all years.

from the LPMS for the months of January and February of each year. Similarly, one ice hardware cycle per day was assumed and added to the computed hardware cycles from the LPMS for the months of January and February of each year.

Using the definition of a lockage cut as the process of passing one cut of a tow or several vessels through a lock, the numbers of lockage cuts on monthly and yearly bases were computed. The numbers of hardware cycles on a daily, monthly, and yearly basis corrected for ice lockages and hardware cycles were computed. The numbers of lockage cuts and hardware cycles are shown in Tables 1 and 2, respectively, on a monthly and yearly basis. These tables indicate the monthly, seasonal, and yearly variations of these quantities. However, since the correlation level between tailwater elevation and

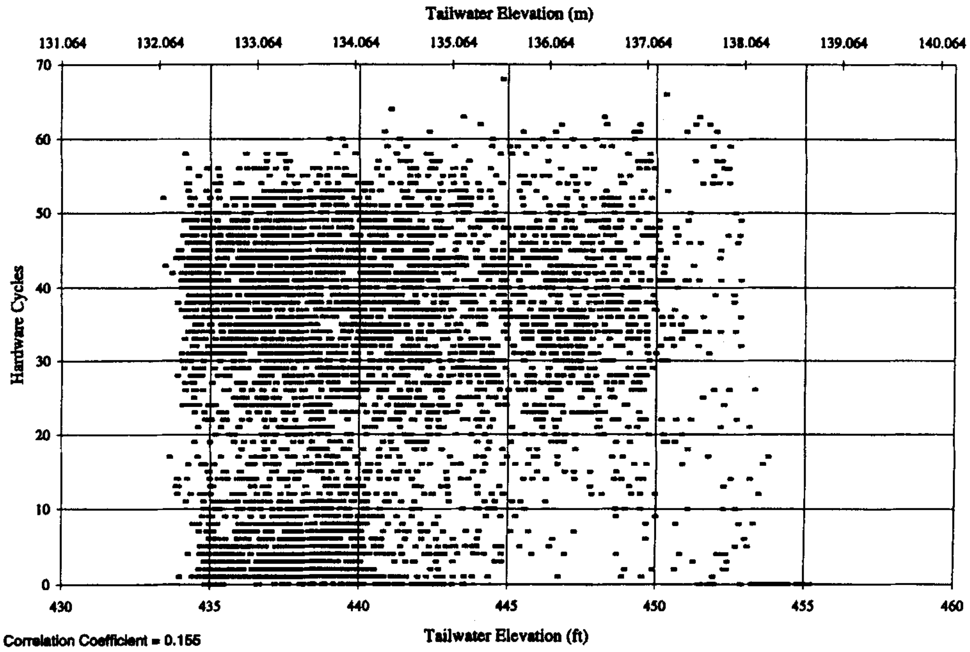


FIG. 5. Daily Tailwater Elevation and Hardware Cycles 1980–94

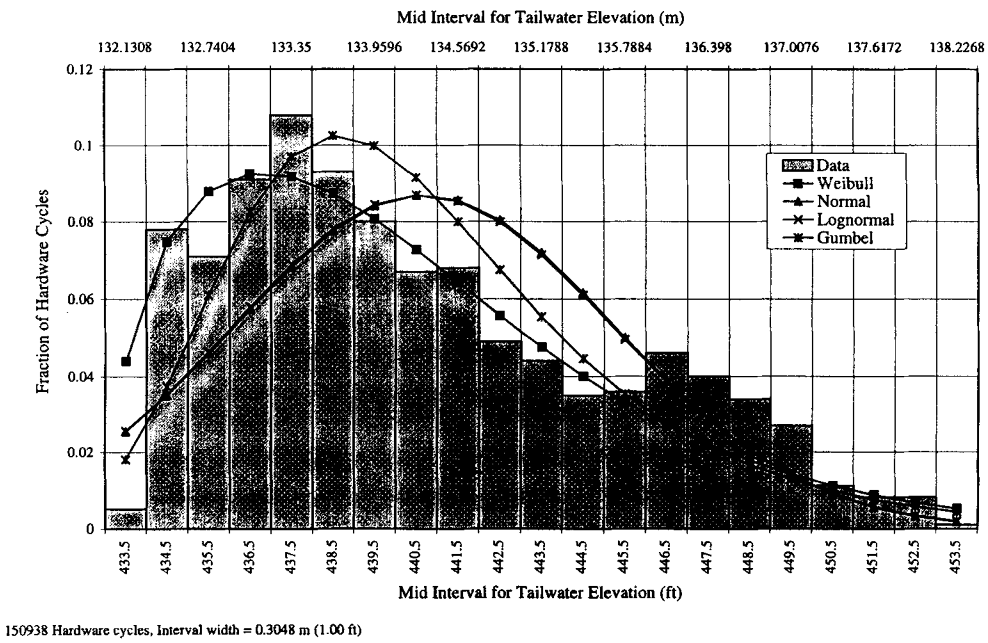


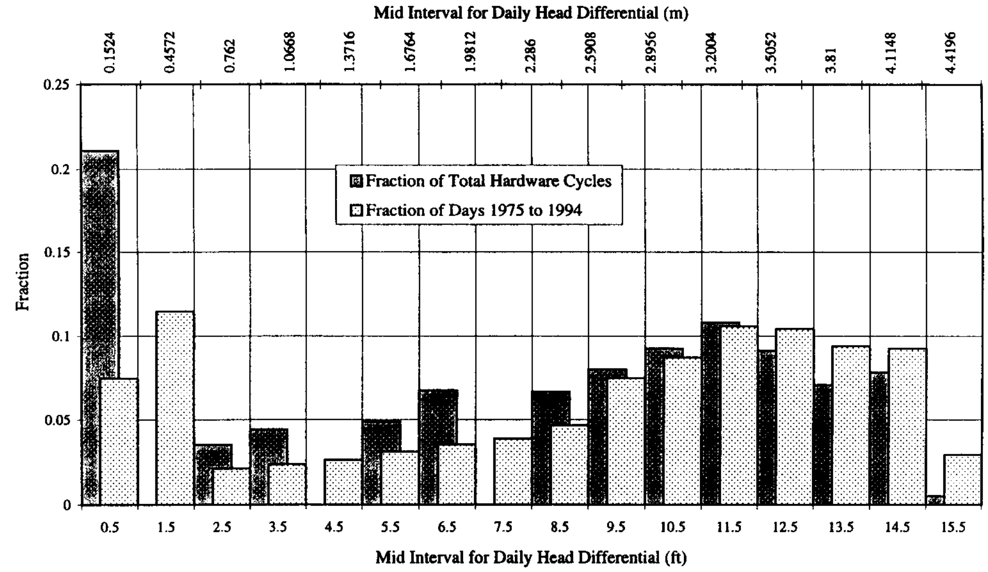
FIG. 6. Histogram of Tailwater Elevation and Fraction of Hardware Cycles with Models

number of hardware cycles was computed to be 0.155, all water-elevation records were aggregated into one model without regard to monthly, seasonal, or yearly variations. This correlation is shown in Fig. 5. Therefore, the number of hardware cycles associated with the same tailwater elevation was aggregated to obtain a histogram (Fig. 6) based on 150,938 hardware cycles. Considering the daily records of tailwater elevations and the corresponding hardware cycles, a weighted average of water elevation was computed to be 134.321 m (440.685 ft). The standard deviation of the weighted tailwater elevation was 1.397 m (4.582 ft). The maximum and minimum water elevations were 138.291 (453.71) and 132.082 m (433.34 ft), respectively.

The resulting histogram can be used to select a probability distribution model, or it can be used directly in reliability and life expectancy analysis. Fig. 6 shows the histogram with four candidate distributions. By examining Fig. 6 and based on the results of the chi-square test, the Weibull distribution can be considered to be the best model among the candidates (Ayyub et al. 1995).

The impact of the results of this study on the fatigue reliability results for the lock was investigated in two forms—its impact on a compound water-head differential (H_d) and its impact on a computed reliability index (β). The former impact assessment is more accurate than the latter one due to approximations used in the latter assessment. The results reported in this section can be considered as a preliminary assessment of the effect of the computed water-elevation and hardware cycles on fatigue reliability. A complete assessment of this impact is recommended for future study.

Daily water-elevation records were used to compute the water-head differential (H_d), and a histogram was developed without regard to load cycles as shown in Fig. 7. The mean head differential was 2.520 m (8.267 ft); the standard deviation was 1.452 m (4.7636 ft); the coefficient of variation was 0.576; and the standard error for the mean was 0.0172 m (0.0565 ft).



150938 hardware cycles in 1980 to 1994 (a record of 7118 days) using an interval width = 0.3048 m (1.00 ft)

FIG. 7. Fractions of Days and Total Hardware Cycles for Water-Head Differential 1980–94

TABLE 3. Impact of Water-Head Differential on Fatigue Reliability

	Water-Head Differential			
Method (1)	Mean [m (ft)] (2)	Standard deviation [m (ft)] (3)	Coefficient of variation (4)	Estimated reliability index (5)
USAEWES (1994)	2.926 (9.600)	1.270 (4.167)	0.434	2.6
Water head only	2.520 (8.267)	1.452 (4.764)	0.576	2.9
Water head and hardware cycles	2.324 (7.624)	1.505 (4.937)	0.648	2.87

By accounting for the daily hardware cycles as weight factors, the histogram was re-evaluated based on Fig. 6 and (28) as shown in Fig. 7. The weighted mean and standard deviation of the water-head differential based on the hardware cycles were 2.324 (7.624) and 1.505 m (4.937 ft), respectively. The coefficient of variation in this case was 0.647. A USACE study (1994) provided estimates of the mean and standard deviation for water-head differential for the same lock of 2.926 (9.600) and 1.270 m (4.167 ft), respectively. These estimates showed that a more rigorous computation of the water-head differential can produce a lower level of head differential due to the effect of hardware cycles.

The statistics of water-head differential were used in the USACE procedure for computing fatigue reliability (safety index) of a vertical beam for a lock as described in Padula et al. (1994). The reliability index was computed as shown in Table 3. The results demonstrate the effect of water-head differential on the estimated reliability index. The results in Table 3 are approximate since only the mean and standard deviation of the water-head differential, not the complete probabilistic characteristics, were used to estimate reliability index.

SUMMARY AND CONCLUSION

Miter gates at navigation locks experience loading cycles due to the emptying and filling of a lock's chamber to assist with the transport of navigation traffic. Assessment of fatigue reliability of existing miter gates at navigation locks as a function of time requires detailed knowledge of past and future loading cycles. A probabilistic model can be used to predict the number of hardware or loading cycles based on vessel traffic or lockage cuts. Loading cycles and stress ranges can be determined from the hydraulic records for pool water and tailwater elevations, and navigation traffic data from the USACE LPMS. Loading cycles can be combined with water-head differentials to obtain loading histograms for miter gates that can be used in the fatigue reliability analysis. From these evaluations the remaining economic fatigue life of the components of a miter gate can be made. An example is shown that demonstrates the development of a loading histogram for a vertical beam component of a miter gate. A preliminary assessment of fatigue reliability based on the explicit computation and use of water elevations and hardware cycles was demonstrated. The extrapolation of this result to fatigue life assessment can be made through the use of cumulative value modeling.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A = model coefficient;
B = model coefficient;
C = model coefficient;
$F_L(l)$ = cumulative distribution function of length of vessel population;
H_d = water-head differential;
H_p = pool elevation (or height) of water;
H_{pn} = normalized pool elevation (or height) of water;
H_t = tail elevation (or height) of water;
H_{tn} = normalized tail elevation (or height) of water;
K = coefficient for expressing seasonal variation in traffic volume and direction;
K_c = mean hardware cycles per lockage cut;
k = number of cuts;
l_{max} = maximum length of vessel that can be locked in one operation of a lock;
N_{cuts} = number of cuts;
N_{HC} = number of hardware cycles;
N_i = number of vessels that are cut into i parts;
N_{loc} = number of lockage cuts;
N_v = number of vessels arriving at lock in time T:
N_1 = number of vessels that are not cut;
NL = number of discrete vessel lengths;
P_i = probability that a vessel is being cut into i parts;
P_1 = probability that a vessel is not being cut into two or more parts;
$p_L(l_i)$ = probability mass value of vessel length;
p_s = probability that a given boat is being serviced simultaneously with other boats;
T = reference time period;
Var = variance;
α = fraction of traffic moving upstream;
β = reliability index;
β_i = fraction of vessels in a month from traffic of a year;
ΔN_{HC} = decrease in mean of total hardware cycles due to simultaneously servicing multiple boats;
ΔN_{HCd} = mean decrease in number of hardware cycles in downstream traffic;
ΔN_{HCt} = mean decrease in number of hardware cycles for two-direction traffic;
ΔN_{HCu} = mean decrease in number of hardware cycles in upstream traffic;
δt = service time in lock for a vessel; and
λ = rate of vessel arrival at a lock.