VII-4. Probability of Failure of Mechanical or Electrical Systems on Dam Gates

Key Concepts

Numerous types of gates are used to release flow from dams. Tainter gates, drum gates vertical lift gates, etc are just a few of the many being used throughout the world. Each gate has its own operating system which must function when needed. Throughout history man has operated gates to control the flow of water. The early Egyptians diverted water by manually opening and closing wood gates. Although the equipment to perform this task has changed greatly throughout history the final results stays the same. Gates must be operated to perform there intended task. To control operation of gates three things must be provided: Power to move the gates, machinery to operate the gate, and the structural gate itself.

Power can be supplied in numerous ways. Manual power is the oldest and supplest means to operate a gate. Manual power references a means by which a human or animal physical provides the energy to move the object, in this case a gate. Modern types of manual devises which are commonly used to move gate are hand wheel, screw actuators. These devises are often mechanized by electric motors which perform the task of providing the power to operate a gate.

The next step up in operation of gates is the electric winch or hoist. These devises are common on gates. Power to operate these types of systems is dependent on electrical service. Almost all dam gates throughout the world rely on some type of electrical service to operate. Because of this, the probability of failure of the electrical system is the first item on any event tree in the potential failure of a gate to operate. The electrical system has numerous components which can fail and prevent a gate from operating. Transformers, circuit breakers, supply wires to name a few. Because of the importance of electrical power at any facility the emergency backup generator has become the standard for redundancy to supply power.

The second critical system which must operate is the machinery. Machinery to operate gates varies as much as the types of gates. Typical gates use winches, hoists or hydraulics to operate. Winches and hoist have numerous types of lifting equipment. They can be manually operated or more commonly electrically operated. Some are even hydraulically operated. The types of lifting devices on winches and hoist vary also. Wire ropes and chains are the most common. Each has its advantages.

The latest means to operate gates is by use of hydraulics. A hydraulic system is dependent on not only electrical power but also hydraulic fluid and the means to transfer the fluid.
The third critical component in any system is the gate itself. For this presentation we will restrict the development of calculating the probability of failure of the system to just the mechanical and electrical systems.

All of these systems have a probability of failure. It’s this probability that will be addressed in this paper.

**Probability of Failure of a System**

Before one can calculate the probability of failure to operate a gate one must know the various components which make up the system and the probability of each component’s failure. To perform this, the most common statistical formula used is the Weibull Distribution formula. Weibull Distribution was developed in 1937 by Swedish born, Waloddi Weibull.

\[
R(T) = e^{-\left(\frac{T-\gamma}{\eta}\right)^\beta}
\]

Where:

- \(R(T)\) = Reliability
- \(T\) = Time
- \(\gamma\) = Location Parameter
- \(\beta\) = Shape Parameter
- \(\eta\) = Characteristic Life
- \(e = 2.718\)

The Weibull formula does not take into account time when components are not in use. Therefore a modified version of the formula called (Dormant-Weibull Formula) is used.

**Dormant-Weibull Formula**

The derivation of the formula was provided to the Corps of Engineers by the Fault Tree software developer, Isograph (Reference Isograph Technical Note 2008.11.13 v1). Also (see equation 4.48 on page 187 of ‘Reliability and Risk Assessment, Henley & Kumamoto’)

\[
Q_n = 1 - \exp \left( \frac{(n-1)T - \gamma}{\eta} \right)^\beta \exp \left[ -\left( \frac{nT - \gamma}{\eta} \right)^\beta \right]
\]

Where:

- \(Q_n\) = Probability of Failure over the entire interval \(n\).
- \(\eta\) = Characteristic Life Parameter
- \(\beta\) = Shape Parameter
- \(\gamma\) = Location Parameter
- \(T\) = Inspection Interval or time since last operated
- \(n\) = Number of times the component operated in its life.

The Dormant-Weibull model is a new failure model that allows the user to model a component or system that undergoes periodic inspection, but is also subject to aging; i.e.
the failure rate increases with time. This model also represents a component whose failure will be revealed due to periodic usage during normal operations.

**Markov Analysis**

This scenario may be modeled precisely using Markov analysis. For the purposes of this document, Markov analysis has been used to generate the unavailability and unreliability profiles.

The model, shown in *figure VII-4-1*, consists of 3 states; a working state, a failed state and an inspection state. The lifetime of the model is split into 2 phases. Phase 1 is the normal operational phase of the model representing the period in between inspections, during which undetectable failures may occur. Phase 2 is a discrete phase (instantaneous transition) that allows the model move from the failed state to inspection, and then to the working state.

![Markov model](image)

**Fig. VII-4-1: The Markov model used to generate the profiles in this document, shown during the operational phase (A) and the inspection phase (B)**

Note that it was not actually necessary to include the inspection state in the analysis. The inspection could have been represented by a single, instantaneous transition from the failed state back to the working state. However, it has been included in the diagram for clarity. The results of the analysis are unaffected.

**Unavailability Profile**

*Figure VII-4-2* shows the unavailability profile for a normal, non-repairable Weibull distribution. The Weibull parameters are $\eta = 100$, $\beta = 2$ and $\gamma = 0$, and the lifetime of the component is 100 (all Weibull distributions represented in this document will have these properties, unless stated otherwise). The distribution is a smooth curve that goes asymptotically towards an unavailability of 1.
When using the dormant Weibull model, the program assumes that the component will be functioning after each inspection takes place; i.e. if the inspection reveals a failure it will be repaired. Figure VII-4-3 shows the unavailability profile for a component, which ages with a single Weibull distribution. In this case the failures are dormant and the inspection period is 20.
Note that after each inspection the unavailability increases rapidly. This is because even though the component is assumed to be functioning after the inspection, the age of the component is unchanged. Hence the failure rate will increase more rapidly after each inspection, reflecting the increasing age of the component.

Whereas unavailability, \( Q(t) \) is defined as the probability of a component being failed at time \( t \), the unreliability, \( F(t) \) is the probability that a component has failed at some point between time 0 and time \( t \). Put simply, the reliability is the probability of the first failure having occurred by time \( t \), assuming the component was working at time 0.

If the age of the component is unaffected by inspections, as is the case in the dormant Weibull model of Fault Tree+, the unreliability profile will be smooth. For this reason, the shape of the unreliability profile for a component modeled using a dormant Weibull model will be smooth, regardless of whether or not inspections take place. See figure VII-4-4.

![Fig. VII-4-4: The unreliability profile for a component modeled using the either the Dormant-Weibull model or Weibull model.](image)

**Fault Tree+ Approximation**

In order to get exact point and mean values of unavailability for a component or system modeled using the dormant Weibull model, it would be necessary to perform a numerical integration over the unavailability profile. However, such a procedure would be highly intensive and thus not practical from a processing standpoint.

In order to overcome this problem, software programs use an approximation to determine these values. Essentially, the program employs the maximum risk dormant model during each interval between inspections. That is, the maximum value of unavailability at the end of each inspection interval is taken to be the unavailability for that period. This is illustrated in figure VII-4-5.
This approach is consistent with fault tree analysis standards.

![Unavailability profile for a component modeled using the dormant Weibull model. The dotted line represents the value of unavailability used by Fault Tree+ for the unavailability during each interval.](image)

**Fig. VII-4-5:** The unavailability profile for a component modeled using the dormant Weibull model. The dotted line represents the value of unavailability used by Fault Tree+ for the unavailability during each interval.

**Results**

For any component that is subject to dormant failures, the introduction of inspections will improve both point and mean values of unavailability. This is because repairs can only take place after inspections due to the dormant nature of the failures.

This can be illustrated by comparing *figures VII-4-2* and VII-4-3. Note that both the point unavailability at the lifetime and the mean unavailability are noticeably less in *figure VII-4-3* where an inspection is taking place at regular intervals, compared to *figure VII-4-2*, which represents a non-repairable component.

Furthermore, more frequent inspections will further reduce the unavailability of the component. This is illustrated in *figures VII-4-6* and *VII-4-7*, which show the unavailability profile for components with identical Weibull parameters, and inspection intervals of 10 and 50 respectively. Note that the component with inspections 10 apart has a lower unavailability than that with inspections 50 apart.
The unreliability is unaffected by the length of the inspection interval. Again, this is because the age of the component remains unchanged by an inspection, regardless of whether a repair is required or not. The only way to change the unreliability profile for such a component would be to alter the Weibull parameters.
Derivation of Unreliability

For an event of failure rate $\lambda(t)$, unreliability $F(t)$ is given by:

$$F(t) = 1 - \exp\left(-\int_{(n-1)\tau}^{n\tau} \lambda(t) \, dt\right)$$

(see equation 4.48 on page 187 of 'Reliability and Risk Assessment, Henley & Kumamoto')

Note that the limits of the integral are $nt$: and $(n-1)$-$T$. This represents non-repairable period between inspections with interval $\tau$. The integral in the above expression is solved as follows:

$$\int_{(n-1)\tau}^{n\tau} \lambda(t) \, dt = \int_{(n-1)\tau}^{n\tau} \frac{\beta(t-\gamma)^{\beta-1}}{\eta^\beta} \, dt$$

$$= \frac{\beta}{\eta^\beta} \left[ \frac{(t-\gamma)^\beta}{\beta} \right]_{(n-1)\tau}^{n\tau}$$

$$= \frac{(n\tau - \gamma)^\beta}{\eta^\beta} - \frac{((n-1)\tau - \gamma)^\beta}{\eta^\beta}$$

Substituting back into the term for the unreliability, $F(t)$, we get the unreliability at the end of an inspection interval, $F_n$:

$$F_n = 1 - \exp\left(-\frac{(n\tau - \gamma)^\beta}{\eta^\beta} + \frac{((n-1)\tau - \gamma)^\beta}{\eta^\beta}\right)$$

$$= 1 - \exp\left(\frac{((n-1)\tau - \gamma)^\beta}{\eta}\right) \cdot \exp\left(-\frac{(n\tau - \gamma)^\beta}{\eta}\right)$$

For a non-repairable component, $F$ is the same as the unavailability (probability of failure on demand), $Q$. Hence,

$$Q_n = 1 - \exp\left(\frac{((n-1)\tau - \gamma)^\beta}{\eta}\right) \cdot \exp\left(-\frac{(n\tau - \gamma)^\beta}{\eta}\right)$$

VII-4-8
Key Elements to using the Dormant-Weibull Formula:

1st Key Element in the Formula

\( \eta = \text{Characteristic life} \)

Definition: The characteristic life is the point in time when we could expect 63.2% of the components under study to have failed.

Example: Its determined that the characteristic life of a component is 25 years, then you would expect to have 63 of 100 components fail by that time in history.

Characteristic life is traditionally gathered through testing of thousands of samples. The problem the Corps encountered is lack of statistical data on failure of its components. To solve this dilemma the U.S. Army Corps of Engineers has performed and extensive data collection of its mechanical and electrical equipment on flood control projects throughout the U.S. From this data collection the actual real world characteristic life of components was determined. For navigation project the Corps used an Expert Elicitation to determine the characteristic life of its components. Over 100 components were evaluated.

When the Corps performed nationwide data collection and its expert elicitation to determine the characteristic life of its components it considered an average components life over the entire range of projects throughout the U.S. with average maintenance. In reality components have a shorter characteristic life in some environments and conditions then others.

Condition is always a factor in determining probability of failure of a component. Inspections of the components are taken into account and a A-F scale is used to rate the condition of the component. A predetermined adjustment factor is used to adjust the characteristic life depending on its condition rating. In addition environment, stress and temperature factors are considered in the characteristic life and adjusted by a predetermined factor.

Example: If a component is showing extreme wear at an early stage of its life then the characteristic life of the component is adjusted down by a predetermined factor. Or if it is exposed to a harsh salt water environment or heavy silt build up.

2nd Key Element in the Formula

\( \beta = \beta \text{ Shape Parameter} \)

\( \beta < 1 \) Implies quality problems or insufficient “Burn In”, usually associated with beginning of a components life.

\( \beta = 1 \) Random failures or failures independent of time in service.

\( \beta > 1 \) Wear out failures at a definite or predictable end of life. Typically age related due to service conditions such as corrosion, wear, or fatigue cracking.

The Corps used Beta Shape Parameter factors from ETL 1110-2-560, dated 30 June 2001, based on the type of failure the component experiences and the data collected on its nationwide data search. Example: Corrosion, wear, fracture, etc.
3rd Key Element in the Formula
\( \gamma = \text{Location Parameter} \)

\( \gamma \) = Location Parameter is the difference in years between when the component was originally installed and when it was replaced. This basically shifts the overall probability of failure curve to represent the actual age of the component if it was replaced sometime in the past.

Example: If a component was originally installed in 1965 and was replaced in 1995 the location parameter would be. 1995 – 1965 = 30 years

If the component is original then the location parameter = 0.

4th Key Element in the Formula
\( t = \text{Inspection Interval} \)

\( t \) = Inspection Interval. Time in (years) between when the component was last inspected or operated properly to present.

Example: A component was last operated 1 month ago.

\( t = 1 \text{ month}/12 \text{ months per year} = .0833 \)

Example using the formula to calculate the probability of failure of a wire rope

The year is 2010 and the wire rope was installed in 1960. Characteristic life of a wire rope is 40 years from U.S. Army Corps of Engineers expert elicitation. Beta shape parameter for wire rope is 3, based on abrasion, corrosive wear, etc ETL 1110-2-560. The wire rope operates in a normal environment and was last operated or inspected 1 month ago. On average the wire wipe operates 12 times a year.

Using the Dormant-Weibull formula:

\( \eta = \text{Characteristic Life} = 40 \)

\( \beta = \text{Shape Parameter} = 3 \)

\( \gamma = \text{Location Parameter} = \text{original wire rope} = 0 \)

\( t = \text{Inspection interval or time since last operated in years} = 1 \text{ month}/12 = .08333/\text{year} \)

\( n = \text{Number of times the component operated in its life} = (2010 – 1960)*12 = 600 \)

Probability of failure:

\( Q_n = 1 - \exp[((600-1)*.0833-0)/40]^3]*exp[-[((600*.0833-0)/40)]^3] = .0097 \) this year

Knowing the probability of failure of an individual component in a system is good but the goal is to find the probability of failure of the entire system which operates a gate. The most common way of analyzing an entire system is with a fault tree software program.
How a Fault Tree works

Each individual component's probability of an event happening/probability of failure is calculated by the fault tree program based on age, condition, when it was last tested or operated, characteristic life, and beta shape parameter for the type of failure. The program is set up in a tree arrangement of the components which make up a system (see fig. VII-4-10). The components combine into what are called gates. The gates represent the probability of the events happening. There are various types of gates but the two most common are (And/Or) gates. (Or) gates – Figure VII-4-8 represents a scenario in which any of the components fail and the entire system fails. (And) gates – Figure VII-4-9 represents systems which have redundancy. Example, three pumps on a hydraulic system in which all three pumps would need to fail for the entire hydraulic system to fail to operate.

Formula for (And Gates / Or Gates)

Or Gate = Q1+Q2+Q3-Q1*Q2-Q1*Q3-Q2*Q3+Q1*Q2*Q3

And Gate=Q1*Q2*Q3
Example of a simple fault tree showing the probability of failure of a wire rope drive system is shown in figure VII-4-10.

There are many software developers which provide fault tree analysis. Reliability Workbench Fault Tree developed by Isograph, demonstrated in this section is only one such software.

Now that we have calculated the probability of failure of the gates at a project we determine how it affects the overall project’s “Risks Assessment” Many scenarios can be developed for risk of failure of a dam one being the movement of gates prevent passing of water through the dam thus possible overtopping of the dam. Event trees are developed to layout the events which occur to cause a failure of the project. The probability of failure calculated earlier is used in the event trees.

Three simple event trees are shown below demonstrating the various ways electrical, mechanical or controls failure could affect risk.
Fig. VII-4-12
Mechanical Drive Fails to Open Gate

Fig. VII-4-13
Controls Fail to Open gate

References

Reliability and Risk Assessment, Henley & Kumamoto

Isograph Technical Note 2008.11.13 v1