RELIABILITY ANALYSIS OF SPILLWAY GATE SYSTEMS

By

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ABSTRACT

The goal of this research is to develop a methodology to accurately determine the reliability of spillway gate systems particularly for spillways that experience harsh environmental conditions and prolonged periods of dormancy. As existing spillway structures become older and more prone to operational failures, spillway gate safety becomes more critical. Empirical evidence demonstrates that the perceived level of reliability of gates overestimates the actual reliability, especially for gates that are operated very infrequently.

The significance of this study lies in the fact that spillways are rarely in use and remain inactive for most of their service life. Components of emergency spillway gate systems spend the majority of their service life in a dormant state and are activated only during emergencies such as floods or load rejection or on a regular basis for inspection and testing. Also, most spillways are located in remote areas and are subjected to severe environmental conditions which can cause early degradation of components. Furthermore, components of old spillway gate systems are often custom made with no readily available spare parts and little information on the reliability of existing components. These characteristics are very different from those of the equipment used in an industrial setting making it difficult for traditional methods to deliver accurate estimates on the reliability of such systems. Therefore, the development of a methodology that is customized to such conditions and incorporates unique parameters and state-of-the-art reliability techniques can contribute greatly to the dam industry by ensuring the safe operation of spillway systems on demand.

This study aims to develop reliability analysis procedures that account for the various functions and characteristics of a spillway including all electrical, mechanical and structural components. One of the main challenges in this evaluation is obtaining realistic estimates for the reliability of individual components. Spillways are usually very unique in their design with poorly documented operational records which renders purely statistical approaches impractical.

The first step in this approach is geared towards system modeling in which a reliability model is developed for the spillway gate system taking into account all components, their

relative interactions, latent failures due to dormancy, environmental conditions and type and frequency of inspections and tests. Fault tree analysis, time-dependent reliability analysis, Markov and semi-Markov analysis are among the techniques used to model the spillway gate system.

The next step is to develop a quantitative approach to update the availability of the spillway gate system based on real time conditions after each inspection. In this step, a Condition Indexing (CI) approach is combined with dormant availability analysis to evaluate the changes in the state of the system in real time using CI data obtained at each inspection. This approach provides a tool for dam owners to convert qualitative and descriptive results obtained from inspections to an index used as a comparative measure to detect real time changes in the availability of spillway gate systems.

Next, inspection and testing procedures of spillway gate systems are investigated to evaluate the effect of different types and frequencies on the reliability of various types of components (electrical, mechanical and structural) and the entire system. Lastly, the optimum inspection and testing strategy is determined, minimizing system costs including costs related to inspection and testing and the consequences of failure while at the same time maintaining the availability of the spillway gate system above a predefined limit. Approaches such as Genetic algorithm and Creeping Random Search are used to solve this optimization problem. Using these methods the optimum interval for each type of test is determined and the minimum system cost is calculated based on the optimum intervals.

This methodology is used to develop a software application that incorporates all of the above steps into a user friendly program. This software application has been developed specifically for availability analysis of spillway systems using object-oriented programming and allows users to model complex systems, add inspection, tests and component replacement options to the system, determine the availability of the system as a function of service life and identify the optimum inspection and testing period based on unavailability limits and costs of inspections/tests vs. consequence of failure.

This program can be used as a tool by dam owners to accurately determine the availability of custom spillways and to select optimal inspection and testing plans that contribute most to increase the availability of the system.

RÉSUMÉ

Le but de cette recherche est de développer une méthodologie pour déterminer avec précision la fiabilité des évacuateurs de barrages en particulier pour les évacuateurs qui sont exposés à des conditions environnementales extrêmes et sont sujets à de longues périodes d'inactivité. Avec le temps, les composants d'un évacuateur deviennent plus âgés et plus susceptibles à des défaillances opérationnelles et la sécurité de l'évacuateur devient plus critique. Les données empiriques montrent que la perception du niveau de fiabilité des évacuateurs surestime la fiabilité réelle, en particulier pour les évacuateurs qui sont exploités très rarement.

L'importance de cette étude réside dans le fait que les évacuateurs sont rarement utilisés et demeurent inactifs pendant la majeure partie de leur durée de vie. Les composants des évacuateurs d'urgence passent la majorité de leur durée de vie dans un état de dormance et ne sont activés que lors de situations d'urgence telles que les inondations ou le rejet de la charge ou sur une base régulière pour l'inspection et des tests. En plus, la plupart des évacuateurs sont situés dans des régions avec accès limité et sont soumis à des conditions environnementales extrêmes qui peuvent causer une dégradation rapide des composants. En outre, les composants de vieux évacuateurs sont souvent fabriqués sur mesure, sans pièces de rechange facilement disponibles et peu d'informations sont disponibles sur leur fiabilité. Ces caractéristiques sont très différentes de celles des équipements utilisés dans un milieu industriel ce qui rend difficile l'application des méthodes d'analyse conventionnelles pour estimer la fiabilité de ces systèmes. Par conséquent, le développement d'une méthodologie qui est adaptée à ces conditions peut grandement contribuer à améliorer la sécurité de fonctionnement des évacuateurs sur demande.

Cette étude vise à élaborer des procédures d'analyse de fiabilité qui considèrent les différentes fonctions et caractéristiques d'un évacuateur, y compris tous les composants électriques, mécaniques et structuraux. L'un des principaux défis dans cette évaluation est d'obtenir des estimations réalistes de la fiabilité de chaque composant. Les évacuateurs sont généralement très uniques dans leur conception avec peu de documentation sur le remplacement des pièces, ce qui rend les approches statistiques inapplicables.

La première étape de cette approche est la modélisation du système en tenant compte de tous les composants, de leurs interactions, des défaillances latentes en période

d’inactivité, des conditions environnementales, du type et de la fréquence des inspections et des essais. L'analyse des arbres de défaillance, l'analyse de la fiabilité en fonction du temps, les processus de Markov et semi- Markov sont parmi les techniques utilisées pour modéliser les évacuateurs.

Une approche quantitative a été développée afin de mettre à jour la disponibilité des évacuateurs en fonction de l’état des composants suite à une inspection. Dans cette approche, une évaluation du niveau de fiabilité des composants est obtenue en fonction d’un diagnostic basé sur des observations qualitatives et quantitatives recueillies lors des inspections. Le modèle utilise cette information et intègre un modèle de détérioration afin de prédire la disponibilité des évacuateurs.

Finalement, les procédures d'inspection et d’essais sur les évacuateurs sont étudiées pour évaluer leur effet sur la fiabilité en fonction de leurs caractéristiques, de leur efficacité et de leur fréquence pour les différents types de composants (électriques, mécaniques et structurels) et l'ensemble du système. Enfin, une stratégie optimale pour les inspections et les essais est déterminée en minimisant une fonction de coûts qui intègre les coûts liés aux essais et inspections et les conséquences d'une défaillance et en respectant une norme minimale de fiabilité. Les algorithmes d’optimisation basés sur algorithme génétique et la recherche aléatoire sont utilisés pour résoudre ce problème. En utilisant ces méthodes, les fréquences optimales sont déterminées pour chaque type d'essai.

Cette méthode est utilisée pour développer un logiciel qui intègre toutes les étapes ci-dessus. Ce logiciel a été développé spécifiquement pour l'analyse de la disponibilité des évacuateurs en utilisant la programmation orientée par objet et permet aux utilisateurs de modéliser des systèmes complexes, ajouter les inspections, les essais et les options de remplacement de composants du système, déterminer la disponibilité du système en fonction de la durée de vie, et identifier les fréquences d'inspection et d’essai optimales.

DEDICATION

To my beloved husband, Alireza for his never-ending patience, support and encouragement

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Dams are among the most essential infrastructures of a country, built for the purpose of impounding water for flood control, water supply, irrigation and energy production. Based on the material and construction method used, dams are divided into two main categories of embankment and concrete dams. An embankment dam is characterized as earthfill if it is comprised of soil and other compact earth materials and rockfill if it's comprised of rocks. Concrete dam are made of concrete and have different types such as gravity and arch dams. The type, size and cross section of dams vary depending on location, climate and amount of water pressure being retained. There are two main types of dams depending on the amount of water storage. Reservoir dams retain water in a reservoir which is a natural or artificial impoundment used to store water for power generation or water supply. Run of the river dams are built across rivers and have little to no storage. The concept of run of the river dams is to build one or more dams on a river in order to create head and control water levels in certain areas along the length of the river for power generation, water supply or recreational purposes.

An essential component of a dam is the spillway system which, by controlling releases, prevents overtopping and reduces impacts associated with excessive downstream flows and upstream water level on infrastructures, the population and the environment. Spillways can be classified either based on function such as main (service), emergency and auxiliary spillways, or mode of control such as uncontrolled and controlled (gated) spillways. Many types of spillway gates exist and selecting a certain type depends on factors such as economics, reliability and accuracy or flood predictions, duration and amount of spillage and type of dam. Some examples of types of gates include: radial gates, drum and sector gates and vertical lift gates (Novak, 2001). The spillway system can perform several dam safety roles: Control flood waters, prevent overtopping during load rejections for run of the river dams, and lower the reservoir level in the event of structural or foundation deficiencies.

Investigations by the US National Research Council for the analysis of causes of embankment incidents and failures show that 2% of events are caused by malfunction of spillways gates (Lewin, Ballard, & Bowles, 2003). This failure rate is generally considered unacceptable based on existing requirements on safety critical installations. A preliminary analysis of gate failures by the US Army Corps of Engineers (USACE) shows that the typical probability of failure on demand of spillway gates in the US is 1 in 10 to 1 in 100. This is high considering that the target safety limit is thought to be of the order of 1 in 10000 (Lewin, Ballard, & Bowles, 2003). Failure of a spillway gate system can be defined as a failure to discharge a required volume of water in a timely manner (dam specific) or the inability to control a release (failure of gate while opening, failure to close a gate, unintended opening of a gate, improper release). Causes of these failures can be attributed to equipment as well as operational failures (ICOLD, 1995). Records show that for about 80% of dams the primary deficiency is due to inadequate spillway capacity (Bivins, 1981). Overtopping of a dam is the most common cause of dam failure. National statistics show that overtopping due to inadequate spillway design, debris blockage of spillways, or settlement of the dam crest account for approximately 34% of all U.S. dam failures. Other causes of dam failures include structural failure of the dam and inadequate maintenance (ASDSO, 2003).

These statistics and the deteriorating state of current dams indicate that spillways are becoming more prone to failure. Since the consequences of dam failure can be catastrophic and can involve loss of life, it is critical to develop procedures to evaluate the reliability and risks associated with spillways and to evaluate mitigation procedures that may also include warning systems.

Researchers have been developing methodologies to ensure the safety of spillway gates both in terms of operation and equipment, and to best allocate rehabilitation resources to the most critical components. Also dam safety guidelines provide instructions and recommendations for operation, maintenance and safety of dams and spillways gate systems (ICOLD, 1995; FEMA, 2010; CDA, 2007). Risk assessment and reliability analysis have been the main focus of recent research conducted in this field. A review of techniques currently used is presented in a report by the USACE (Putcha & Patev, 2000). One of the main challenges in this evaluation is obtaining realistic estimates for the reliability of individual components. Spillways are rarely in use and remain inactive for most of their service life. Hence, components of most spillway gate systems spend the majority of their service life in a dormant state and are activated randomly (i.e. for high flows or load rejection) or on a regular basis for inspection and testing. Also, most spillways are located in remote areas and are subjected to severe environmental conditions which can cause early degradation of components. Furthermore, components of old spillway gate systems are often custom made with no readily available spare parts with little information on their reliability. These characteristics are very different from equipment used in an industrial setting making it difficult for traditional data bases to deliver accurate estimates on the reliability of such systems.

1.1 RESEARCH OBJECTIVES

The main objective of this thesis is to develop a methodology and the related software application to accurately determine the reliability of spillway gate systems. The first step in this approach is to develop a reliability model that takes into account all mechanical, electrical and structural elements of the spillway gate system and their relative interactions while also incorporating the effect of component dormancy, environmental exposure and regular inspections and tests on the overall reliability of the system. To ensure that the gate is operable when required, it is important to determine the probability of failure on demand of the system as a function of time. As most spillway gates are dormant and failure of a component is not identified until the system is activated and since they are primarily safety systems, it is more appropriate to use the availability of the system as an alternative to reliability.

The second step is to develop a quantitative approach to update the availability of the spillway gate system based on real time conditions after each inspection. In this step, the Condition Index (CI) approach previously developed by the USACE (Estes, Foltz, & McKay, 2005) has been modified to accommodate degrading and aging of the system and account for component dormancy. The Dormant CI approach updates the system availability using data obtained after each inspection. This approach provides a tool for dam owners to convert qualitative and/or quantitative information obtained from inspections to quantify changes in the availability of spillway gate system.

The third step is to determine the effect of inspection and tests on the availability of spillway gate system in order to identify the most effective inspection and testing plan both in terms of cost and increase in system availability. Spillway systems spend the majority of their life in a dormant state; therefore, it is critical to conduct periodic inspections and tests to ensure their safe operation. Preventive maintenance operations usually include visual examination of the component, cleaning and lubrication where necessary and are conducted to facilitate smooth operation of the components and should be performed according to the procedure recommended by the manufacturer. Over time, even with regular inspection and maintenance, the dormant nature of the system along with the severe environmental conditions to which spillways are exposed, may result in the degradation of performance of components. Therefore, testing the functionality of the gate is an important aspect in ensuring continuous safe operation. The type and frequency of inspections and tests of spillway gate facilities used to assess the performance level of various components represent a major commitment of financial resources and personnel for dam owners. FEMA (2010) and USSD (2002) present a thorough overview of spillway gate systems and review industry guidelines for the evaluation of maintenance, inspection and testing procedures of spillway gate components. These activities and the information that is collected in this process should be considered when evaluating the in-service availability of the spillway gates.

The final step of the approach is to determine an optimum inspection and testing plan for the spillway gate system which minimizes system costs including costs related to inspection and testing as well the consequences of failure while at the same time maintaining the availability of the spillway gate system above a predefined limit. Dam owners are obligated to ensure that the availability of the spillway gate system remains within certain limits. This limit is determined based on consequence of failure which includes population at risk, injury or loss of life, property damage and environmental effects downstream of the dam. These consequences are categorized in dam classifications and standards used by dam owners. The main approach used to solve this optimization problem is Genetic Algorithm through which the cost function is minimized with the availability limit as a constraint. Using this method, the optimum interval for each type of test is determined and the minimum system cost is calculated based on these optimum test intervals.

After the methodology is completed, the next objective is to develop a software application using Visual Studio® 2012 that incorporates all the steps of the methodology into a user friendly program. With this software application, users will be able to navigate easily through menus and dialog boxes to model a spillway gate system comprised of electrical, mechanical and structural components, add dormancy, environmental effects and inspection and test options to each component and determine the availability of each component as well as the entire system as a function of time. Also the software application has a built-in optimization option and the optimum inspection/testing plan for a given spillway and minimum system costs can be determined by providing inspection/testing costs and failure consequences. This software application has been developed specifically for availability analysis of spillway gate systems and is expected to contribute greatly to the dam industry by determining the availability of the spillway gate and its components, evaluating the effects of different inspection and testing strategies on system availability and determining the optimum inspection/testing plan for a given spillway.

1.2 THESIS ORGANIZATION

After the first introductory chapter, an overview of spillway gate systems including spillway gate types and guidelines on the operation, maintenance, inspection and testing of gates is presented in Chapter 2. This chapter also includes a review of existing dam classifications, the basic concepts of reliability analysis required in the development of the methodology including literature on dormancy and environmental condition modeling and a comprehensive review of the current research conducted on the reliability of spillway gate systems. Furthermore, a summary of reliability analysis programs as well as a review of optimization techniques used to optimize maintenance, inspection and tests is also presented in this chapter.

Chapter 3 is a journal article by the author (Kalantarnia, et al., 2012), which describes the dormant availability analysis approach using condition indexing. The article explains the concept of condition indexing and its combination with the dormant availability theory to develop a quantitative index from qualitative and descriptive inspection results as a measure to determine the current state of the system and to project the condition of the system in the future. This approach has been developed to make use of the regularly conducted inspection results and to obtain more precise estimate of the condition of the system. At the beginning of the service life of the system, each component has an estimated life span and availability, however, due to dormancy and environmental conditions, components may deteriorate slower or faster than expected. This method provides information on the current state of the system after each inspection. This allows dam owners to obtain updates on the availability of the system and to project its future conditions and to verify whether or not the behavior of the system is as expected. This method can be very beneficial to the dam industry and at present, if conducted regularly throughout the lifetime of a system, can act as a comparative measure to identify changes in the condition of the system as it deteriorates; however, in order to use this approach effectively, CI data must de compiled to calibrate failure rates as a function of CI. Therefore, the method is expected to improve with time as more data on CI and performance are obtained.

Chapter 4 contains a second journal paper by the author introducing the software application developed for the purpose of modeling and analyzing the availability of spillway gate systems. This article presents the methodology used in the program including Markov/semi-Markov analysis to model electrical, mechanical and structural components and latent failures during dormancy, the use of K-factors to incorporate environmental condition, the effect of type and frequency of inspections and tests on the availability of each component and fault tree analysis used to model the system and component interactions. The article also contains instructions on the use of the software application and evaluation of the results. The case study presented in this paper illustrates a complete model of a vertical lift spillway gate with all components and interactions and the unavailability of the system throughout its service life. The unavailability of different types of components (electrical, mechanical and structural) is also presented to show how unavailability varies based on component type, probability distributions, environmental and dormancy factors and type and frequency of inspections/tests.

The final journal article by the author presented in Chapter 5 describes possible applications of the methodology and program on spillway gate systems. The first part of this article evaluates to effects of type and frequency of inspection and tests on the availability of electrical and mechanical components. It also determines the maximum allowable intervals between inspections and tests based on unavailability limits established by dam classifications and standards. The second part of the paper models an entire spillway system comprised of a combination of gates both with individual and common lifting mechanisms. This section determines the availability of a spillway system with a specific inspection and testing strategy relative to potential failure scenarios such as load rejection and flooding. This study provides essential information to dam owners to select appropriate inspection and testing strategies to ensure spillway system operability during critical events. Finally, the last part of this paper discusses the methods used in the optimization of inspection and test interval to minimize system costs including both inspection/test costs and consequence of failure while maintaining average system availability above predefined availability limits. Results are compared for dams classified as low and high consequence.

Conclusions of this study and recommendations for future work are presented in Chapter 6.

Appendices:

- Appendix A: Condition Index Tables
- Appendix B: Condition Index Values of Spillway Gate Components
- Appendix C: Failure Rates of Spillway Gate Components

Chapters 3 to 5 are prepared as individual journal articles; therefore, the overlap seen in the content of these Chapters is to maintain their technical integrity and completeness. Details of the journal articles presented in these sections are as follows:

- Chapter 3: Application of Dormant Reliability Analysis to Spillways (2013), Journal of Infrastructure Systems, 20(1), 04013003
- Chapter 4: Availability Analysis Software Application for Spillway Gate Systems (2013), Journal of Computing in Civil Engineering, (Submitted- Manuscript No: CPENG-1152), Status: under review
- Chapter 5: An Objective Procedure for the Optimization of Inspection and Testing Strategies for Spillways (2013), Journal of Infrastructure Systems, (Submitted- Manuscript No. ISENG-631), Status: under review

Contributions of the co-authors of these journal articles include supervision of research, technical review of the articles and providing real-world data for case studies.

CHAPTER 2: REVIEW OF RELEVANT CONCEPTS

This chapter presents a comprehensive overview of the methodologies and concepts adopted in this study as well as a review of the existing literature in each relevant field. This chapter begins by an overview of spillway gate systems including gate types and their advantages/disadvantages, guidelines on gate operation and recommendations on maintenance, inspection and testing of gate components. Next, a review of existing dam classifications and standards is presented followed by a comprehensive review of current literature available on the reliability of spillway gate systems. This is followed by basic concepts and methods of reliability analysis required in the development of the methodology in this study including literature on dormancy and environmental condition modeling. Furthermore, a summary of reliability analysis programs that can be used to model spillway gate systems as well as review of optimization techniques used to optimize maintenance, inspection and tests are also presented in this chapter.

2.1 SPILLWAY GATE SYSTEMS

Various types of gates are in operation worldwide. The shape and size of these gates depends on factors such as capacity of the reservoir, dam and spillway type, duration of spillage, flood prediction and environmental conditions. The design of spillway gates usually includes several main components such as skin plate which is the component that holds back and supports the water load, structural framing which are the columns and girders supporting the skin plate, anchorage which transfers the load from the gate frame to the support structure, seals which are placed in between two surfaces to prevent water leakage, operating mechanism which opens or closes the gates using a hoist mechanism or hydraulic/pneumatic actuators and electrical power which is the primary source of power for gate operation (USSD, 2002).

2.1.1 SPILLWAY GATE TYPES

This section will describe the most common types of gates available in the dam industry:

2.1.1.1 VERTICAL LIFT GATES

Vertical lift gates are rectangular in shape and move up and down vertically through the spillway opening with the use of rollers or wheels which transfer the horizontal hydrostatic load to the pier slots. Hoist mechanisms such as lifting screws, chain, and wire ropes and pulleys are typically used for operation of these gates. The lifting mechanism used for these gates may be dedicated or travelling (common between multiple gates) which is mounted on a gantry crane.

These gates are generally used when the elevation of the upper pool is very high. Vertical lift gates are simple in design with short construction and assembly time; however, friction between wheels or rollers increases over time producing excessive bearing pressure which may lead to jamming of the rollers or wheels during operation. Regular maintenance is critical for this type of gate to ensure that rollers and wheels are rust free, lubricated and are able to rotate freely and without excess friction (USSD, 2002). Figure 2-1 shows the gate structure and lifting mechanism of a vertical lift spillway gate system.

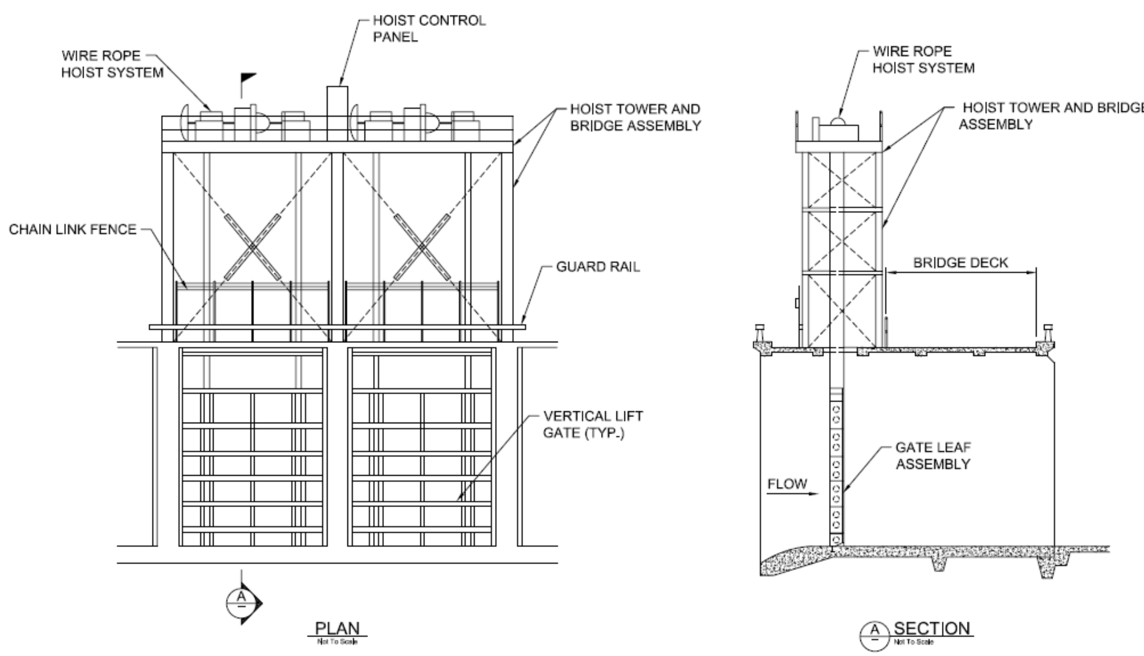

Figure 2-1: Vertical lift gate and lifting mechanism drawings (Alberta Transportation, 2004)

2.1.1.2 RADIAL GATES

Radial gates also known as tainter gates consist of a curved skin plate reinforced by beams and supported by vertical and horizontal girders. The gates rotate about two trunnions located at the center of curvature of the skin plate arc on a horizontal axis on the downstream side. It is important to locate the trunnions above maximum flood water surface to avoid contact with floating ice and debris and to avoid submerging the components (USSD, 2002). The operating machinery for radial gates is located above the gate and typically includes wire rope hoists, chain hoists, or hydraulic cylinders (FEMA, 2010). Figure 2-2 shows a hydraulically operated radial gate system.

Radial gates are very common as they are economical to build and very reliable. They are also light weight and require less hoist power to operate. However, these types of gates are not recommended for large dams and dam sites which have tail water elevations as the trunnions should remain above flood water levels. Also specific environmental conditions such as excessive cold may indicate the use of other types of gate as freezing of the trunnions can be very problematic for the operation of the gate.

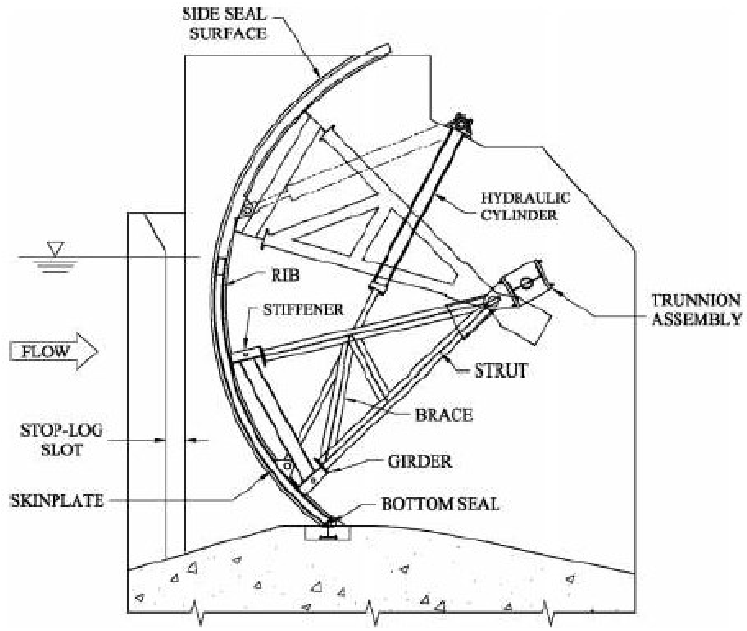

Figure 2-2: Hydraulically operated radial gate (FEMA, 2010)

2.1.1.3 HINGED CREST GATES

Hinged crest gates consist of reinforced skin plates with the inner side of the plate conforming to the profile of the spillway crest. The gate is hinged at the bottom and is opened and closed by rotating the plate down and up respectively. The gate is closed in the fully raised position. The operating equipment of the gate consists of multiple hydraulic cylinders placed either downstream or on adjacent piers on top of the plate. However, downstream mounted cylinders are subject to damage by trash in water passing over partially open hinged crest gates. Figure 2-3 shows a hinged crest gate with hydraulic cylinders mounted of the top of the gate.

Hinged crest gates are very common as they are economical to build. However, they have size and capacity limitations and are mainly used on smaller dams and they are seldom large (over 3m) due to the high hoisting capacity required or lower the gate through overflow (USSD, 2002).

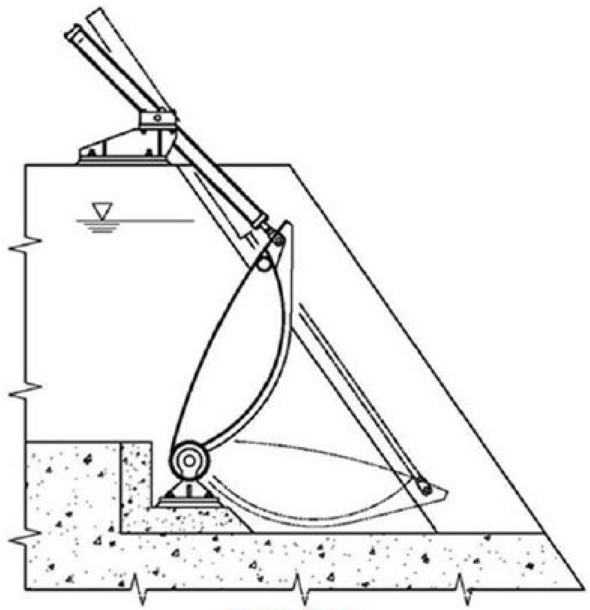

Figure 2-3: Hinged crest gate (FEMA, 2010)

2.1.1.4 DRUM GATES

Drum gates are horizontally oriented floating vessels that operate using the principle of buoyancy. The skin plate side of the drum is reinforced with internal bracing. In the fully lowered position, the drum sits inside a chamber immediately downstream of the crest called the control chamber; hence the drum surface becomes flush with the spillway crest covering the opening of the control chamber and creating a clear flow path. The drum gate is operated by the application of headwater pressure beneath the gate. When the gate is to be raised, the control chamber is filled with water from the upstream side. The gate weight is overcome by buoyancy and the gate is forced to rise. To lower the gate, water is drained from the control chamber (FEMA, 2010). Figure 2-4 shows an upstream hinged drum gate.

Drum gates were more common prior to the 1950s and they are no longer considered practical in modern spillway gate design due to difficult maintenance, complex sealing, lack of good operational control, leakage and high building and maintenance costs. However, this type of gate may still be found in many large dams and are still required to operate in the future.

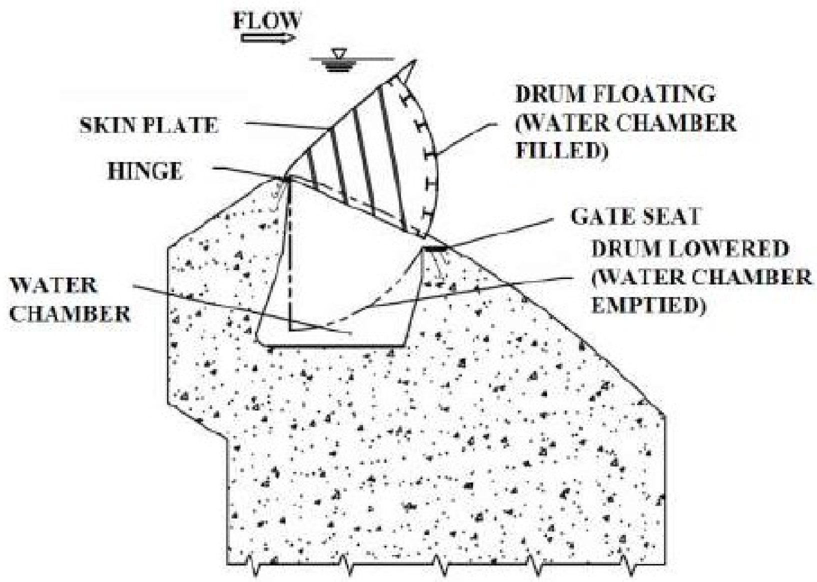

Figure 2-4: Upstream hinged drum gate (FEMA, 2010)

2.1.2 GUIDELINES AND RECOMMENDATIONS ON MAINTENANCE, INSPECTION AND TESTING OF SPILLWAY GATES

There are generally two critical failure scenarios of a spillway gate: operational and structural failure. Operational failure is due to gate, hoist or control problems, resulting in loss of spillway flow regulation. According to the United States Society on Dams (USSD), operational failure itself may lead to the inability to close a gate resulting in the loss of valuable water supply or the inability to open a gate resulting in reservoir overflow and ultimate breaching of dam. Structural failure may result in uncontrolled release of water to downstream channels, which may lead to potential property damage and loss of life, and loss of valuable water (USSD, 2002). To avoid failure and ensure safe operation of the spillways, institutions such as USSD, the Federal Emergency Management Agency (FEMA) and the International Committee on Large Dams (ICOLD) have developed guidelines and instructions for maintenance, inspection and testing of the gate components.

Once spillway gate components are designed and built, most of them are either hidden from view or located at hard to reach places (submerged or above the crest). Therefore, long term, reliable gate operation requires knowledge of the aging condition of all gate components and regular inspections, maintenance, tests and repair when required.

2.1.2.1 MAINTENANCE

Component manufacturers usually provide manuals documenting recommended maintenance activities. These documents need to be made available to the maintenance personnel when conducting such activities. FEMA recommends preparing a comprehensive maintenance manual for the entire gate with reference to hoisting and operating equipment including a list of parts requiring periodic replacement, lubrication and other maintenance activity schedules. According to FEMA, a maintenance manual should include information such as installation instructions, operation and criteria, maintenance instructions for electrical, mechanical and control components, part list, drawings and diagrams and safety instructions. FEMA also recommends preparing a complete maintenance record document containing detailed information of all maintenance activities, repairs and modifications (FEMA, 2010).

A spillway gate is comprised of a variety of mechanical and electrical components. For electrical components, routine maintenance usually includes a thorough check of electrical panels to ensure they are free of moisture and dirt and wires are free of corrosion and mineral deposits, adjustment and replacement of box heaters and light bulbs, verification of tightness of bolted connections and test of the system to ensure all parts function properly. The main electrical components of a gate include the emergency generator, hoist motor, power supply and control systems (FEMA, 2010).

Main routine maintenance activities for mechanical component of a gate include:

- Lubrication: Gate and hoist components such as bearings, connection points, gears, wire ropes, chains and other moving or rotating devices require regular lubrication to maintain their smooth operation. A common cause of wear or corrosion can be lack of lubrication or contaminated lubrication. Over time due to exposure to environment, lubricants can be contaminated with sand, dust, dirt or water. FEMA recommends that during maintenance, all lubricants be checked for proper level, water build-up, contamination and lubricity which is the measure of a lubricant's ability to continue providing lubrication (FEMA, 2010). More information on lubricants and lubrication may be found UASCE EM 1110-2-1424, Lubricant and Hydraulic Fluids.

- Removal of trash and debris: Flow of water through the spillway opening may be accompanied by floating and submerged trash that can affect the functionality of the gate. Trash and debris may build-up and add to the lifting weight of the gate and cause other issues such as jamming or binding of the gate during operation. Hence it is important to clean build-up debris and trash as needed during periodic maintenance of the gate.
- Cleaning: Over time, grit, sand and dirt and residue build-up will collect in bearings, brakes and sealing surfaces. FEMA recommends regular cleaning of mechanical components with the use of soft cloths and compressed air to avoid unwanted damage and reduced performance.
- Alignment and adjustment: Rough, noisy or erratic movement during operation is the first sign of a developing problem. Periodic adjustment and realignments are necessary to ensure smooth gate operation. FEMA recommends that hoist components such as gear box and brakes be checked regularly during maintenance for adverse or excessive wear and missing parts and for worn or corroded parts to be replaced.

Other general maintenance activities of spillway gates may include touch up painting, sealing surfaces and the application of de-icing fluids.

2.1.2.2 INSPECTION

Visual inspection is the simplest way to obtain general information on the condition of an existing gate. It is important for inspection activities to be well documented using checklists and updated instructions and for findings and corrective actions to be recorded. It is also essential for inspection activities to be conducted regularly in accordance with an established inspection schedule. Design documents, construction history, operation history and previous inspection records need to be at hand when preparing for an inspection. The type and frequency of inspection for each gate depends on gate type, usage requirements, hazard classification of the dam, regulatory requirements and consequences of gate failure such as downstream property damage, loss of life and environmental damage (FEMA, 2010). FEMA recommends the following types of inspections to be conducted regularly:

- Informal: A general, non-specific visual inspection for issues which may have developed since the previous inspection including visual inspection of the hoist deck, access ladders and platforms. This type of inspection may be conducted during routine maintenance.
- Intermediate: A walkthrough inspection that looks for obvious deficiencies of the gate and operating system but does not include a detailed close-up inspection of the structural and mechanical components.
- Periodic: Includes a more thorough observation of the gate and operating system. A team composed of different disciplines such as electrical, mechanical and structural need to be present to perform this type of inspection.
- Close-up: Major structural and operating system component are visually inspected close-up and in detail. This is to ensure that small defects such as cracks, missing nuts and bolts and signs of wear and corrosion in mechanical components are detected.
- Unscheduled: May be required for unusual deficiencies or problems in between regular inspections.

For structural components, FEMA recommends inspections to begin by a visual observation of the gate and presence of accumulated unwanted materials such as water, debris or vegetation. Later, missing, distorted, or broken structural members and connections need to be identified. It is also important to look for signs of corrosion at high risk locations such as dissimilar metals in contact or areas in the splash zone or submerged in water. Inspection of the coating of members for signs of flaking, powdering, peeling or debonding is critical when looking for corrosion. Another important item in the inspection of structural components is signs of aging. Structural components become brittle with age; therefore, it is essential to look for signs of aging such as fatigue cracks during visual inspection. Other inspection activities for structural elements include: identification of components with signs of cavitation, examination of the skin plate and support structure for misalignment, indentation, corrosion, warping, twisting and buckling, examination of structural connections such as bolts, rivets, pins and welds for missing, broken or loos parts and signs of rust and corrosion. Furthermore, the seals should be inspected to ensure they are intact, flexible and not excessively deformed or torn (FEMA, 2010).

Operating system components consist of hoisting equipment, power sources and gate controls. For electrical and control instruments, FEMA recommends that all controls, instrumentation, breakers and electrical panel boards and switchboards be opened and inspected, wiring and wire terminations should be looked at for signs of damage and breakers and fuses should be verified for proper rating and functionality. For mechanical components, FEMA also recommends to look for signs of distress such as missing gear teeth, gearbox and bearing noise, noticeable vibration, loose baseplates and misalignment. For example, shafts and couplings must be free of cracks or pitting with the coupling tight and bolts intact, gears should be well lubricated with no missing teeth or signs of damage, corrosion or misalignment and brakes should be properly adjusted and free from contaminations such as sand, dirt or material residue.

2.1.2.3 PERFORMNCE TESTING

The most comprehensive method to verify the operation of gates is to operate them under a full range of operational conditions at design load levels; however, actual gate raising under full hydrostatic load is not always practicable due to financial costs associated with head loss and/or downstream consequences; therefore, other options such as partial gate opening or full opening with no hydrostatic load using stop logs are recommended.

Partial-travel testing is defined as opening of the gate to 10% of its full travel path under full hydrostatic load. FEMA recommends that these types of tests be performed annually. Satisfactory partial-travel gate operation generally gives a good indication that hoist components are in adequate condition since maximum loading often occurs during unseating of the gate. However, it does not verify the ability of the gate to physically operate through its full travel without binding or jamming.

FEMA also recommends conducting full-travel tests using stop logs at least once every 5-10 years. This type of test mostly addresses structural deficiencies of the gate such as misalignments, missing components, jamming or blockage. Satisfactory stoplog test operation generally indicates that the structural components are in adequate condition;

however, it does not verify the ability of the hoist components to operate under full hydrostatic load.

Tests should be scheduled prior to flood seasons or periods when high flows are expected to ensure gate operability in case of emergencies. Apart from the performance testing of the spillway gate system, components such as the emergency power generator should also be tested to verify functionality at shorter time intervals.

2.2 DAM CLASSIFICATIONS

As dams increase in number and size, legislation and regulations to insure their long-term safe operation has gained increasing importance. International guidelines and recommendations covering the safety of dams have been published which recommend that national authority should be empowered to examine and approve all stages of design, construction and repair of dams and be responsible for approving operation and surveillance schedules (ICOLD, 1987).

In the US, federal dams are subjected to control through government agencies, e.g. USACE or the US Bureau of Reclamation (USBR). Together, these federal agencies are responsible for five percent of the dams in the U.S. They construct, own and operate, regulate or provide technical assistance and research for dams (Novak, 2001). Non-federal dams are subjected to legislation in most states. Today, every state except for Alabama has dam safety regulatory programs. State governments have regulatory responsibility for 80% of the approximately 84,000 dams within the National Inventory of Dams. Typically, the program activities include: safety evaluations of existing dams, review of plans and specifications for dam construction and major repair work, periodic inspections of construction work on new and existing dams and review and approval of emergency action plans (ASDSO, 2003).

In Canada the Canadian Dam Safety Association (CDSA) was founded in 1989 to advance the implementation of practices to ensure the safe operation of dams. In 1997, the CDSA joined the Canadian National Committee on Large Dams (CANCOLD) to form the Canadian Dam Association (CDA). The CDA has developed technical bulletins on topics such as dam safety guidelines, surveillance of dam facilities and failure consequences of dams. According to the CDA, classification of dams based on consequences or risk of failure provides guidance on the standard of care expected of dam owners (CDA, 2007). Table 2-1 presents dam classifications according to the CDA.

Table 2-1: Dam classifications based of failure consequences defined by the Canadian Dam Association (CDA, 2007)

Dam class	**Population at risk**	**Incremental losses**		
		Loss of life	**Environmental and cultural values**	**Infrastructure and economics**
Low	None	0	Minimal short-term loss, no long-term loss	Low economic losses, area contains limited infrastructures or services
Significant	Temporary only	Unspecified	No significant loss or deterioration of fish or wildlife habitat, Loss of marginal habitat only, Restoration or compensation in kind highly possible	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes
High	Permanent	10 or fewer	Significant loss or deterioration of important fish or wildlife habitat, Restoration or compensation in kind highly possible	High economic losses, affecting infrastructures, public transportation and commercial facilities
Very high	Permanent	100 or fewer	Significant loss or deterioration of critical fish or wildlife habitat, Restoration or compensation in kind possible but not practical	Very high economic losses affecting important infrastructures or services (e.g. highways, industrial facilities, storage facilities for dangerous substances)
Extreme	Permanent	More than 100	Major loss of critical fish or wildlife habitat, Restoration or compensation in kind impossible	Extreme losses affecting important infrastructures or services (e.g. hospitals, major industrial complex, major storage facilities for dangerous substances)

Other classifications, e.g. provincial regulations for the province of Quebec, consider population density, nature of human activity, characteristics of the affected area and extent of damaged infrastructures (Government of Quebec, 2002). According to the Dam Safety Regulations of Quebec, "*every dam must be classified on the basis of the degree of risk it poses to persons and property, measured by multiplying the numerical value of its vulnerability (V) by the numerical value of the potential consequences of a dam failure (C) to which "P" is the assigned value in the formula P = V x C*" (Government of Quebec, 2002). In this formula vulnerability (V) is the mean value of physical parameters of the dam such as dam height, type, impounding capacity and dam foundation type multiplied by the mean value of variable parameters such as age, seismic zone, condition and effectiveness of maintenance activities. Table 2-2 shows dam classifications as a function of the P value based on the dam safety regulations of Quebec.

Table 2-2: Dam classifications based of P value defined by the Quebec dam safety regulations (Government of Quebec, 2002)

P Value	**Dam Class**
$P \geq 120$	A
$70 \leq P < 120$	B
$25 \leq P < 70$	C
$P < 25$	D

Consequences of dam failure are based on downstream population density, extent of infrastructures and services that would be destroyed or severely damaged. Table 2-3 lists the dam failure consequence categories.

Table 2-3: Dam consequence categories and description based of the dam safety regulations of Quebec (Government of Quebec, 2002)

Consequence Category	**Description**
Very Low	Uninhabited area OR Area containing minimal infrastructures or services such as: a second dam in the Very Low Consequence category, a resources access road, farmland, a commercial facility without

	accommodations
Low	Occasionally inhabited area containing less than 10, cottages or seasonal residences OR Area containing a commercial facility that provides, accommodation for less than 25 persons or that has, less than 10 accommodation units (i.e., 10 cottages, 10 campsites, 10 motel rooms) OR Area containing limited infrastructures or services such as: a second dam in the Low Consequence category, a local road
Moderate	Permanently inhabited area containing less than 10, residences or occasionally inhabited and containing, 10 or more cottages or seasonal residences OR Area containing a seasonal commercial facility that, provides accommodation for 25 or more persons or that contains 10 or more accommodation units or that operates year-round and provides accommodation for less than 25 persons or has less than 10 accommodation units OR Area containing moderate infrastructures or services such as: a second dam in the Moderate Consequence category, a feeder road, a railway line (local or regional), an enterprise with less than 50 employees, a main water intake upstream or downstream of the dam that supplies a municipality
High	Permanently inhabited area containing 10 or more residences and less than 1,000 residents OR Area containing a commercial facility that operates year-round and provides accommodation for 25 or more persons or has 10 or more accommodation units OR Area containing significant infrastructures or services such as: a second dam in the High Consequence category, a regional road, a railway line (transcontinental or transborder), a school, an enterprise that has 50 to 499 employees
Very High	Permanently inhabited area with a population of more than 1,000 and less than 10,000 OR Area containing major infrastructures or services such as: a second dam in the Very High Consequence category, an autoroute or national highway, an enterprise that has 500 or more employees, an industrial park, a dangerous substances storage site

Dam classifications based on consequence categories provide guidelines for dam owners to develop tools and strategies in order to maintain the reliability of their dams in an acceptable and safe range depending on the dam classification.

2.3 RELIABILITY ANALYSIS OF SPILLWAY GATE SYSTEMS

Reliability analysis and risk assessment play an important part in ensuring the safety and continuous operation of spillway gate systems. This section reviews current techniques and methodologies used by practitioners for the reliability analysis and risk assessment of dams and spillway systems.

2.3.1 FLOOD AND RESERVOIR SAFETY INTEGRATION

The Department of Environment, Food and Rural Affaires (DEFRA) in the UK have developed a methodology for risk analysis of dams as part of a research program on reservoir safety in the UK. This approach had one principal overall objective which may be summarized as: "*propose and demonstrate an Integrated System which provides a framework for decision making by panel engineers on the annual probabilities of occurrence, consequences and tolerability of all the various threats to reservoir safety*" (DEFRA, 2002).

This approach was part of a feasibility study on quantitative risk assessment for dams in general and was not specific to spillway gate systems. The approach used in this research is to rank and quantify threats to dam safety using data from visual inspection and desk studies. Figure 2-5 shows the algorithm applied in this method.

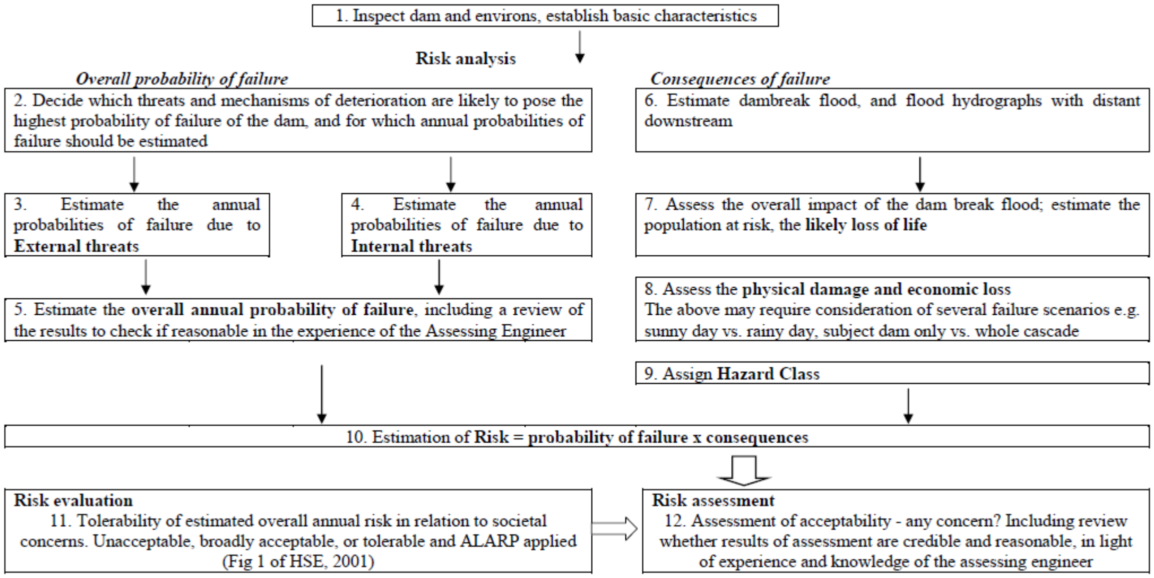

Figure 2-5: Overview of prototype integrated system (DEFRA, 2002)

The approach comprises the following steps (DEFRA, 2002):

1- Determine the definition of failure: failure is defined as uncontrolled sudden large release of water which could compromise the safety of the population or operational failure, which could interrupt the supply from the dam.

2- Identify all the potential threats to dam safety and consider the extent to which these threats are independent or interdependent. These potential threats are categorized into internal and external threats.

- External threats are loads such as floods and earthquakes which are random natural events which could trigger failure of the dam.
- Internal threats are mainly due to the deterioration of the dam either time dependent or under reservoir load or some flaw which requires a prolonged loading period or number of loading cycles to lead to failure.

3- Determine the probability of a threat occurring: annual probability of failure due to threat or by failure mode

$$APF_{ALL}^{FM} = \frac{Number\ of\ failures\ in\ period\ considered\ due\ to\ threat\ or\ failure\ mode}{Number\ of\ dam\ life\ years\ in\ period\ considered \times C_1} \quad [2\text{-}1]$$

Here C_1 is the % of dams with data, which is an estimate of the percentage of dams in the database for which the data on failures is complete.

4- Rank dam threats and where possible quantify the annual probability of dam failure and the annual probability of each threat occurring, for UK dams.

5- Determine the consequences of failure: assessing the consequences of a dam failure is a prerequisite to defining tolerable risk. It therefore summarizes factors relevant to the determination of the potential loss of life in the event of a dam failure.

6- Determination of risk: $Risk = \sum Probability \times Consequence$

Tolerable risk of dam failure is then determined using techniques such as FN Curve (frequency of occurrence vs number of persons harmed), ALARP (As Low As Reasonably Practicable), etc.

2.3.2 RISK EVALUATION AND RANKING OF SPILLWAYS BASED ON OPERATIONAL SAFETY

This approach developed by Hydro Quebec ranks spillways according to their ability to react safely based on structural characteristics and importance, impact of failure, component vulnerability and present condition of the structure (Briand, et al. , 2009).

Functional safety is viewed as the combination of three indices:

- H-Index: Sufficiency of the hydraulic and hydrologic design of the structure. This is a measure of the optimum state rather than the current functionality of the spillway. Scenarios considered for this index are the passage of safety flood (H-C) and power tripping under full load (H-D).
- V-Index: Vulnerability of the spillway to hydrological and operational risks. This index measures the vulnerability of the spillway to events of negative impact that may occur during operations related to the passage of safety flood (V-C) or in power plant tripping conditions (V-D).

- F-Index: Present condition of the structure and its components based on observations of mechanical and electrical and structural systems. Scenarios of this index are the present condition (F-A) and the impending condition of the spillway in the event of a breakdown caused by observed defects (F-P).

Each index is determined by testing several scenarios of operation measuring the impact of different parameters. The scenarios are tested by simulating a flood-routing. The simulations are run for the safety flood, summer-fall flood and power tripping conditions. Probability of occurrence of an event is considered through weight factors. Scenarios are assigned weight classes based on their frequency of occurrence (Frequent, occasional, rare and exceptional). Table 2-4 shows the classification of scenarios relative to each index. Three levels are defined above the maximum operation level within the reservoir.

- Comfort zone: between maximum operation level (MOL) and maximum extraordinary level (MEL)
- Discomfort zone: the zone between MEL and safety flood level (SFL).
- Alert zone: extends up to the dam safety level (DSL)

For a given scenario when the water level falls in one of these three zones the "percentage of encroachment" is converted into grades from A-D. Table 2-5 shows the conversion of percentage of encroachment to grades.

Finally, a grade is given to each index based on the lowest grade of its scenario and the overall grade of the spillway is the lowest grade among the indices. Table 2-6 show an example of the grading technique.

Table 2-4: Probability classification of scenarios (Briand et al., 2009)

Index		Type		Scenario		Probability
H	H-C	Hydrology		Spring Safety Flood		Occasional
				Summer-fall Safety Flood		Occasional
	H-D			Plant tripping		Frequent
V	V-C	Storage		Flood routing without winter draw-down		Occasional
		Hydrology	Increased flood volume	Flood volume increased by 10%		Occasional
				Flood volume increased by 20%		Rare
				Flood volume increased by 30%		Exceptional
			Increased flood rate	Flood increase rate 10 times faster		Occasional
				Flood increase rate 20 times faster		Rare
				Flood increase rate 100 times faster		Exceptional
		Response Time	Increased mobilisation time	Mobilisation time 3 times slower		Occasional
				Mobilisation time 6 times slower		Rare
				Mobilisation time 11 times slower		Exceptional
			Increased gate operation time	Gate operation time 5 times slower		Occasional
				Gate operation time 10 times slower		Rare
				Gate operation time 15 times slower		Exceptional
		Spilling equipment	Reduced spilling capacity	Spilling capacity reduced by 5%		Occasional
				Spilling capacity reduced by 10%		Rare
				Spilling capacity reduced by 15%		Exceptional
			Reduced gate number	1 gate not functional		Rare
				2 gates not functional		Rare
				3 gates not functional		Exceptional
			Reduced number of hoists	Left hoist not functional		Exceptional
				Right hoist not functional		Exceptional
				Two hoists not functional		Exceptional
	V-D	Increased mobilisation time in response to plant tripping		Mobilisation time twice slower		Frequent
F	F-A	Present		Flood	Gate with 2 m max opening	Occasional
				Plant tripping	Gate with 2 m max opening	Frequent
	F-P	Impending		Flood	Gate with 2 m max opening	Rare
				Plant tripping	Gate with 2 m max opening	Occasional

Table 2-5: Example of a weighting procedure (Briand et al., 2009)

Probability of occurrence	Encroachment	Safety Zone	Grade
Frequent	if level is less than 50%	Comfort	A
	if level is less than 100%	Comfort	B
	if level is less than 25%	Discomfort	C
	if level is greater or equal to 25%	Discomfort	D
Occasional	if level is less than 100%	Comfort	A
	if level is less than 50%	Discomfort	B
	if level is less than 100%	Discomfort	C
	if level is greater or equal to 100%	Discomfort	D
Rare	if level is less than 100%	Comfort	A
	if level is less than 75%	Discomfort	B
	if level is less than 25%	Alert	C
	if level is greater or equal to 25%	Alert	D
Exceptional	if level is less than 100%	Comfort	A
	if level is less than 100%	Discomfort	B
	if level is less than 75%	Alert	C
	if level is greater or equal to 75%	Alert	D

Table 2-6: Example of a general ranking of spillways (Briand et al., 2009)

Spillway	H-Index	V-Index	F-A Index	F-P Index	General Ranking
No 1	A	A	A	A	A
No 2	A	B	A	C	C
No 3	B	C	B	B	C
No 4	B	B	D	D	D
No 5	B	C	D	D	D

2.3.3 FAILURE MODE, EFFECT AND CRITICALITY ANALYSIS (FMECA)

The U.S Army Corps of Engineers has investigated the feasibility of different risk assessment techniques for spillway gate systems (Putcha, et al., 2000). FMEA is recognized as a basic tool to evaluate the reliability of a system in its early stages of design. This approach was first proposed by Dhillon and Singh (1981). This procedure is used to determine if changes in design are required and to evaluate the effect of potential design modifications on risks. FMEA becomes failure modes, effects, and criticality analysis (FMECA) if criticalities are assigned to failure mode effects. FMECA is a bottom-up, inductive analysis that systematically details risks on a component-by-component basis and essentially consists of the following steps (Ebeling, 1997):

- System definition: system components that will be subjected to failure are identified.
- Identification of failure modes: the observable manner in which a component fails is identified.
- Determination of causes: the probable cause(s) of failure is determined. Typical causes can be:
    - Friction: common cause of failures in belts, gears, and machinery in general
    - Contamination: Dirt can cause electrical failure
    - Corrosion: chemical change that weakens material

It is important to note that a failure mode may have more than one cause.

- Assessment of effects: impact of each failure on the operation of the system is assessed.
- Classification of severity: a severity class is assigned to each failure mode. Generally, there are 4 severity classes:
    - Catastrophic: loss of life, major damage
    - Critical: complete loss of system
    - Marginal: system degradation, partial loss of performance
    - Negligible: no adverse effects
- Estimation of probability of occurrence: the expected number of occurrences over a specified period of time is estimated. When sufficient data is not available Military Standard MIL-STD-1629A (MilitaryStandard, 1980) is used for qualitative grouping of failure mode frequencies over the operating time interval:
    - Level A: Frequent - High probability of failure ($p \geq 0.20$)
    - Level B: Probable - Moderate probability of failure ($0.10 \leq p \leq 0.20$)
    - Level C: Occasional - Marginal probability of failure ($0.01 \leq p \leq 0.10$)

- Level D: Remote - Unlikely probability of failure ($0.001 \leq p \leq 0.01$)
- Level E: Extremely Unlikely - Rare event ($p \leq 0.001$)

- Computation of criticality index: this is a quantitative measure of the criticality of the failure mode that combines the probability of the failure mode's occurrence with its severity ranking.

  $$C_k = \alpha_{kp} \beta_k \lambda_p t \qquad [2\text{-}2]$$

  Where C_k is the criticality index for failure mode k, α_{kp} is the fraction of the component p's failures having failure mode k (i.e. the conditional probability of failure mode k given component p has failed), β_k is the conditional probability that failure mode k will result in the identified failure effect, λ_p is failure rate of component p and t is the duration of time used in the analysis (Putcha, et al., 2000).

- Determination of corrective actions: corrective actions are determined and prioritized based on the failure modes having the highest criticality index and severity classification.

2.3.4 RISK ANALYSIS OF DAM GATES AND ASSOCIATED OPERATING EQUIPMENT USING FAULT TREE ANALYSIS

In pursuit of the optimum risk assessment approach for spillway gate systems, the U.S Army Corps of Engineers investigated the feasibility of detailed fault tree analysis to spillways (Putcha, et al., 2005). The objective of this work was to demonstrate how fault tree analytical methods may be applied to improve the quality of dam gate risk analysis.

"Fault trees are one of the most important and simplest methods that can be used to help in the risk assessment of dam gates. These gate systems are often quite complex and detailed, with various types of structural, mechanical, and electrical equipment" (Putcha, et al., 2005). A fault tree for spillway gates is shown in Figure 2-6. The top event is failure of the gate to open or close. As this top event is itself an intermediate event of another tree, the triangle at the top of this figure relates to the contribution of this event to

the main top event which is the overall spillway risk. The goal of these fault trees is to define a highly detailed representation of the fault environment so that the user can rapidly eliminate or accept branches on the basis of pre-screening and background knowledge of the specific dam project.

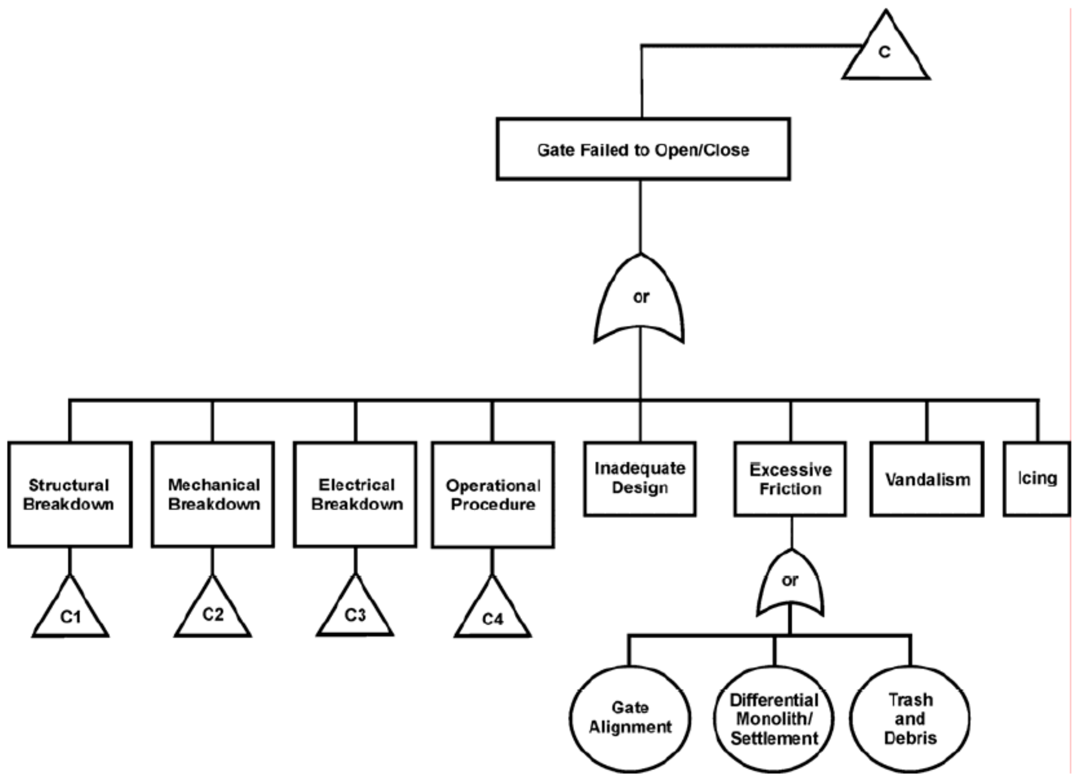

Figure 2-6: Fault tree for gate failure (Putcha, et al., 2005)

The triangles C1 to C4 in Figure 2-6 also relate to other detailed trees representing structural, mechanical, electrical components and operational procedures which may be seen in Figure 2-7 to Figure 2-10.

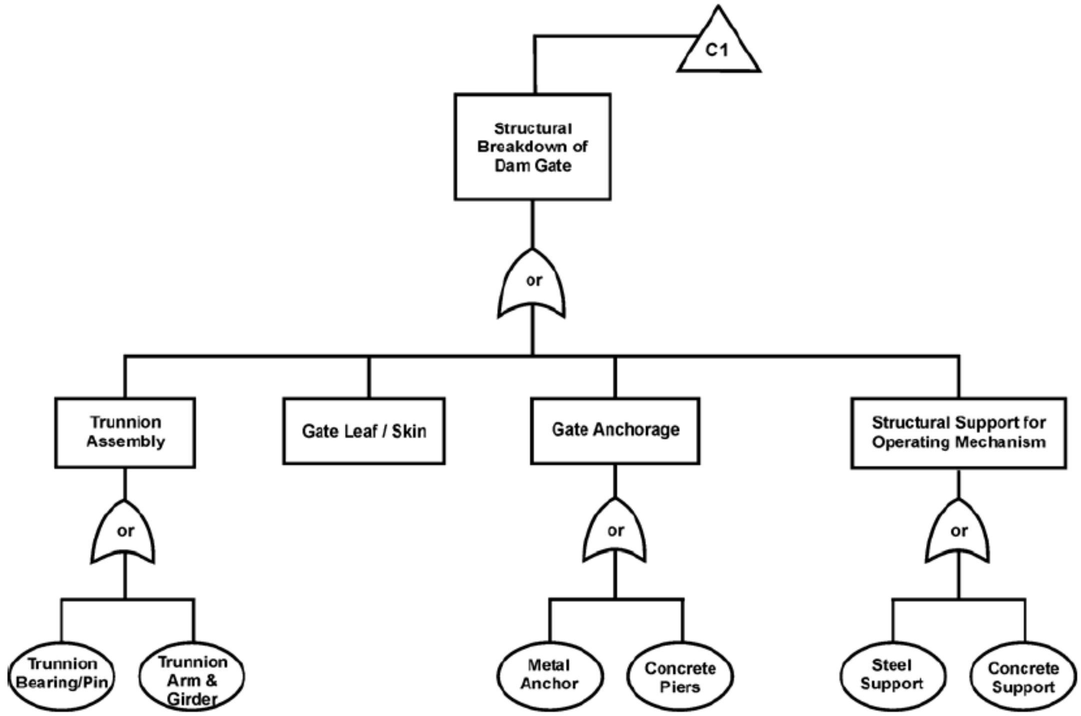

Figure 2-7: Fault tree for gate structural breakdown (Putcha, et al., 2005)

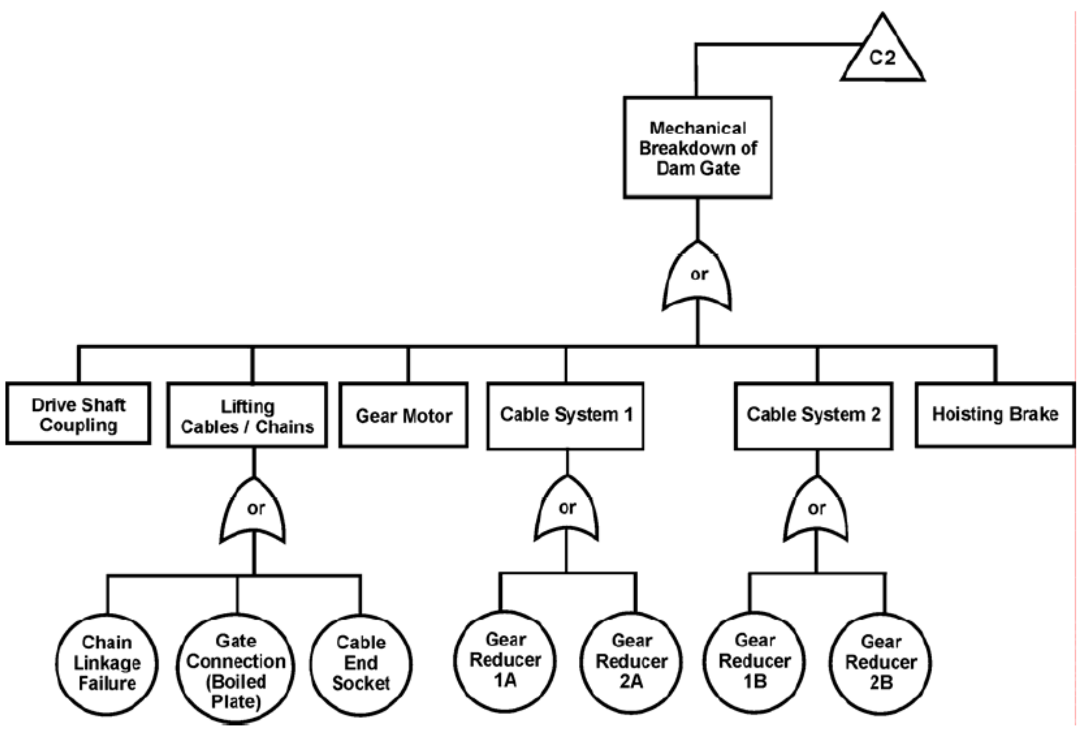

Figure 2-8: Fault tree for gate mechanical breakdown (Putcha, et al., 2005)

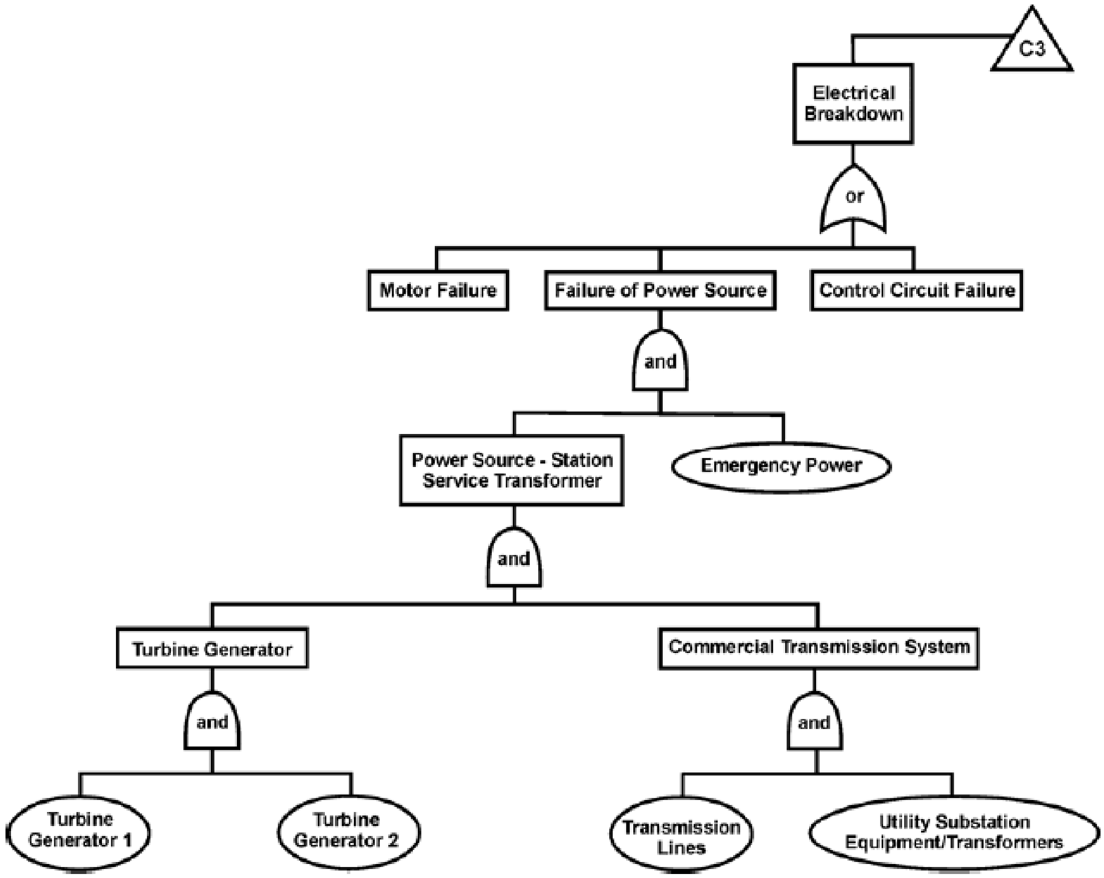

Figure 2-9: Fault tree for gate electrical breakdown (Putcha, et al., 2005)

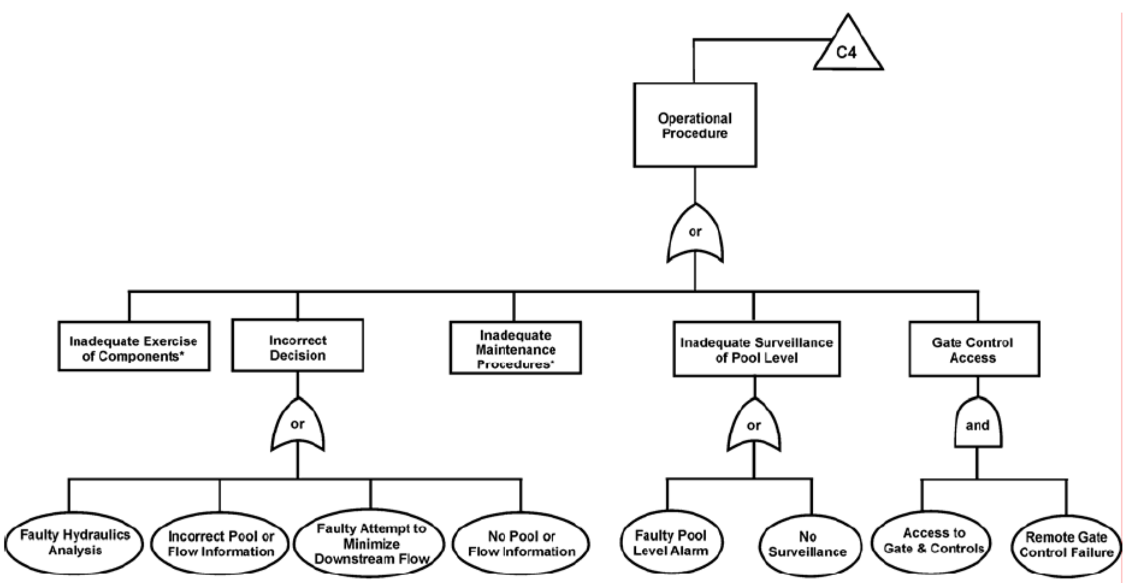

Figure 2-10: Fault tree for gate operational breakdown (Putcha, et al., 2005)

To determine the occurrence probability of the top event, the failure rates of basic causes (events represented in circular shapes) are required. These rates, represented by λ, may be obtained from the performance history of existing or similar gate components or, if no specific data is available, from compiled data in MIL-STD-1629A or other MIL-STD documents (MilitaryStandard, 1980).

In this approach, each event is also assigned a criticality index and a weighting factor. Similar to FMECA analysis discussed in section 2.3.3, the criticality index is a relative measure of the consequence of an event and its frequency of occurrence. The importance factor signifies the relative importance of each component in each event gate.

Assuming component independence and an exponential reliability model for each components, the failure probability of each gate can be determined using the following equations:

AND Gate: $$\mathrm{PF} = \prod_{i=1}^{n} \mathrm{PF_i} = \prod_{i=1}^{n} (1 - e^{-\lambda_i t}) \quad [2\text{-}3]$$

OR Gate: $$\mathrm{PF} = 1 - \prod_{i=1}^{n} (1 - \mathrm{PF_i}) = 1 - \prod_{i=1}^{n} e^{-\lambda_i t} \quad [2\text{-}4]$$

where λ_i and $\mathrm{PF_i}$ are the failure rate and the probability of failure of the i^{th} event of the branch respectively.

Failure rates may be obtained from the literature or data base of similar components. It is important to adjust the failure rate to the condition of the component. An approximate approach (Green, et al., 1972) multiplies failure rates by various K factors to relate the data to other conditions of environment and stress where K is the environmental factor adjustment coefficient used to represent component stress levels altered by environmental conditions. Typical K factors are shown in Table 2-7.

Table 2-7: Environmental K-factors (USACE, 2006)

Table D-1
Overall Environment Component Stress Levels (data from Greene and Bourne 1972)

General Environmental Condition	K_1
Ideal, static conditions	0.1
Vibration-free, controlled environment	0.5
General purpose ground based	1.0
Ship	2.0
Road	3.0
Rail	4.0
Air	10.0
Missile	100.0
Stress Rating	
Percentage of component nominal rating	**K_2**
140	4.0
120	2.0
100	1.0
80	0.6
60	0.3
40	0.2
20	0.1
Temperature	
Component temperature (degrees C)	**K_3**
0	1.0
20	1.0
40	1.3
60	2.0
80	4.0
100	10.0
120	30.0

Note: Other data sources such as Reliability Analysis Center (1995) also contain environmental information.

where K1 relates to the general environment of operation, K2 to the specific rating or stress of the component, and K3 to the general effect of temperature. Similar values of K3 should be developed for cold regions where temperatures below zero may induce adverse effects of components.

The typical failure rates are adjusted in the analysis to the environmental conditions as shown below:

$$\lambda' = K_1 K_2 K_3 \lambda \qquad [2\text{-}5]$$

Where λ' and λ are the adjusted and general failure rates respectively. With the failure probabilities of each component known and considering the weight factors the probability of the failure of the top event for the case of OR gates is:

$$P[\text{Main failure mode}] = \sum_{i=1}^{n} W_i PF_i \qquad [2\text{-}6]$$

where W_i is the weight factor assigned and PF_i is the probability of failure of each subsystem (mechanical, electrical, etc.) (Putcha, et al., 2005). With the failure probability of each failure mode known, the risk of the system can be determined.

Knowing the consequence of occurrence of the top event (based on dam classifications), the risk associated with the failure of the gate to operate (open or close) may be determined. The equation below is a general equation for risk (Lafitte, 1993):

$$R = PD^a \qquad [2\text{-}7]$$

Where *P* is the probability of occurrence of an unwanted event (here, the top event of the fault tree), *D* is the consequence of failure and *a* is the risk consequence factor which is a value typically taken between 1 and 2. With sufficient data available risk associated with a spillway gate can be determined over its lifetime.

2.3.5 ESTIMATING RISK FROM SPILLWAY GATE SYSTEMS ON DAMS USING CONDITION ASSESSMENT DATA

Condition Indexing is a state-of-the-art approach in reliability analysis of spillway gates. This procedure defines the spillway gate system of a dam as a hierarchical structure consisting of systems, subsystems, and components. The overall condition based on component inspection results allow a condition index to be computed at every stage of the structural hierarchy (Chouinard, et al., 2003).

In another report, the U.S. Army Corps of Engineers investigate whether this existing Condition Indexing (CI) methodology for spillway gate systems on dams can be used as a basis for assessing structural risk and probability of failure (Estes, et al., 2005).

Condition indexing assessment is an effective method for accounting for every critical aspect of structural behavior. CI is based on a series of observations by an inspector that is related to a set of objective condition criteria. The advantages of this approach are:

- Standardize approach to quantifying conditions

- Identification of specific problems in the structure
- Establishment of a database for the deterioration of a class of structures
- Prioritization and efficient allocation of scarce maintenance funds
- Guidance for less experience inspectors on what to look for

Condition indexing technique is almost entirely based on reliability analysis methods. Therefore, before discussing this approach a brief overview of reliability analysis terms are required:

- Limit state equation: governs the behavior of the structure.

$$\text{Limit state equation:}\ C - D \geq 0 \qquad [2\text{-}8]$$

Where C is the capacity and D is demand on the system.

- Reliability Index: is a measure of the reliability of a system. For normally distributed independent variables, the reliability index is defined as :

$$\beta = \frac{\mu_C - \mu_D}{\sqrt{\sigma_C^2 + \sigma_D^2}} \qquad [2\text{-}9]$$

where μ and σ are the mean and standard deviation respectively.

- Failure probability: given the reliability index , the failure probability is obtained as:

$$p_f = \phi(-\beta) \qquad [2\text{-}10]$$

where Φ is the distribution function of the standardized normal variable.

The CIs focus on observable deviations from a desired condition. In this report Estes et al. propose an approach in which condition index is treated as a random variable, making initial assumptions that would eventually be modified over time as a database is established, and using existing condition state definitions so that current methods and accumulated data remain valid (Estes, et al., 2006).

CI is considered as a random variable. The probability of failure is the probability that the actual CI rating is lower than the CI rating that defines failure:

$P_f = P(CI_{Actual} \leq CI_{Failure})$

Assumptions:

- CI values are normally distributed and independent
- The parameters (mean and standard deviation) of the actual condition index will be determined by the component condition table and the confidence of the inspector to correctly assign the correct condition state to an inspected component.
- The inspector will classify the structure correctly 95% of the time (Estes, et al., 2005). This 5% inspector error is equally distributed on the high and low sides of the distribution.
- The structure is assumed to transient linearly through the condition states as a function of time.

Failure is assumed to correspond to CI with a distribution $\sim N[25, 12.5]$ corresponding to the states of poor, very poor and failed.

After an inspection, a condition state is assigned to the system based on the current state of the structure.

When a component is first assigned to a condition state, the CI value is assumed to be the midpoint of the range of each condition state. Depending on the service life of the component, it will degrade with a constant rate until it reaches a new condition state in which the CI value will jump to the midpoint of the next state. Therefore at each year the CI may be calculated using the equation below (Estes, et al., 2005):

$$CI_{year\ X} = MAX \begin{cases} CI_{mid} - \dfrac{(CI_{mid} - CI_{min})X}{(\frac{D_{Life}}{\#CS} - 1)} \\ CI_{min} \end{cases} \qquad [2\text{-}11]$$

where CI_{mid} is the condition index at the midpoint of the condition state, CI_{min} is the lowest condition index in the condition state, D_{Life} is the intended design life of the structure, #CS is the number of condition states that the structure will transition through. This equation shows that the $CI_{year\ X}$ value cannot fall below$\mathrm{CI_{min}}$, until an inspection rating indicates that the structure is in a lower condition state.

Using yearly CIs the reliability index may be determined using the following equation (Estes, et al., 2005):

$$\beta_{\mathrm{year\ X}} = \frac{\mathrm{CI_{year\ X}} - \mathrm{CI_{failure}}}{\sqrt{\sigma^2_{\mathrm{year\ X}} + \sigma^2_{\mathrm{failure}}}} \qquad [2\text{-}12]$$

Hence, the failure probability may be determined using the standardized normal distribution function.

The main advantage of this approach is that the failure probability of the system can be obtained using only site inspection and does not require input data on system reliability which are not readily available. The shortcoming of this method is that it should be calibrated with historical performance data that correlates with CI.

2.3.6 THE SPILLWAY SYSTEM RELIABILITY PROJECT

In 2010, the spillway system reliability project was defined and initiated by a group of sponsors from hydropower and dam industries of various countries such as Elforsk from Sweden, the USACE from the US and BC Hydro and Ontario Power Generation from Canada (Baecher, et al., 2013).

Objectives of this project include (CWG, 2010):

- To consolidate existing knowledge on the function of spillway gate systems
- To develop scientific and engineering bases for the assessment of safe discharge of inflows from a system perspective
- To establish a methodology for spillway risk assessment
- To develop system based guidelines for the safe discharge of inflows and water retention

This project includes an approach to analyzing flow-control systems. This approach addresses the operation of flow-control systems as a systems engineering problem and uses simulation to track the interactions among systems components. The modeling framework involves simulation by which stochastic reservoir inflows are generated and propagated through the river/reservoir-spillway-outflow system, engineering modeling to infer the impact of spillway heads and discharges on the hydraulic structures accommodating outflows, component reliability analysis to ascertain the performance of individual components of the outflow works and systems reliability assessment through which demands of the river system and performance of flow-control systems components coupled with interactions of humans are convolved into annual exceedance probabilities of adverse performance (Baecher, et al., 2013).

For spillway gate reliability analysis, engineering reliability modeling is used to evaluate the performance of a component in relation to the demand function. For the structural subsystem, the performance of the components is described in fragility curves, expressing the component's probabilistic behavior as a function of the demand placed upon it (Baecher, et al., 2013). Mechanical and electrical equipment are modeled using block diagram analysis and fault tree analysis.

2.4 DORMANT FAILURE ANALYSIS

Dormant failure is the failure of a system in dormant state, in other words, it is defined as the probability that a system in dormant state will fail prior to a specified time. Safety systems such as alarms, safety valves and spillway gates experience large periods of dormancy throughout their life cycle. Determining the effects of dormancy on such systems is crucial as failure in dormant state will not be identified until they are re-activated. Below are some of the existing approaches on dormant failure analysis:

2.4.1 MARKOV CHAIN ANALYSIS

This method is generally used to determine the reliability of a system as it transits between several states. The main application of this method is to model the behavior of stand-by/redundant systems or systems undergoing deterioration.

This method may also be used to model dormant states of systems by assuming operating, failure while operating, dormant and failure while dormant states for each component and then evaluating system reliability as components transit from one state to the other as a function of time. This approach has also been used to model failure due to degradation for dormant components (Hokstad, et al., 1996). This method while effective in representing dormancy can become increasingly complicated as the system becomes more complex. Figure 2-11 shows a Markov Chain model for two components experiencing failure when active (detected failure) and failure while dormant (undetected failure). It may be seen from this figure that even for a simple system of two components, this model can become very complicated (Hildebrandt, 2007). Therefore, for a large system such as a spillway which is composed of many electrical, mechanical and structural components, care must be taken with the strategic use of this model to avoid complex, time consuming calculations.

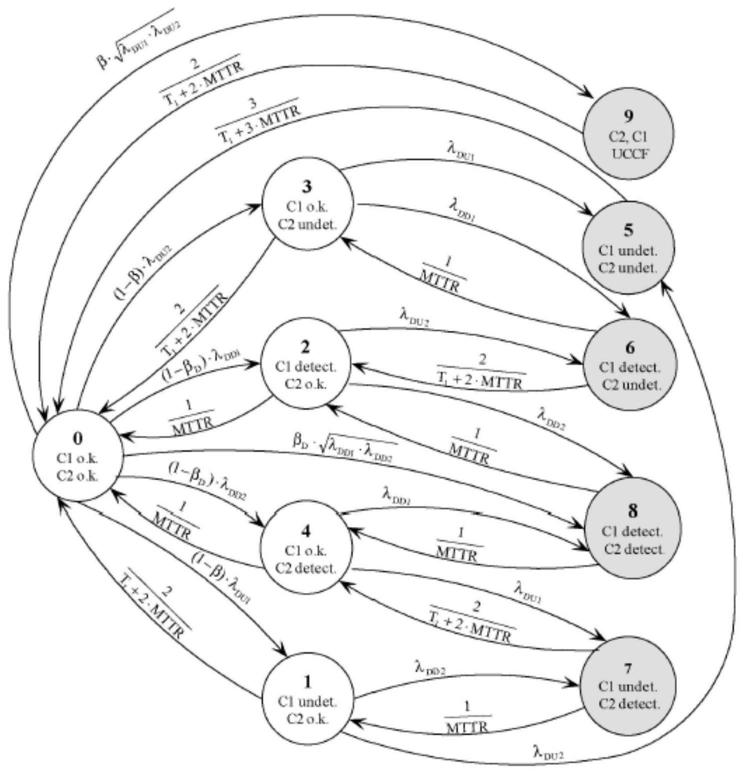

Figure 2-11: Markov diagram for a two component system (Hildebrandt, 2007)

For spillway gate systems, particularly emergency spillways that only operate during emergencies or performance testing, it is reasonable to assume that most failures occur in a dormant state. These types of failures are called latent failures and will not be identified until the system is operated. Therefore to model the electrical or mechanical components two states can be considered: 1) fully operational (active state) and 2) state of latent failure (failed state).

Weibull and exponential distributions are most commonly used to model the time to failure of components. The cumulative distribution function for the Weibull function is:

$$F(t) = 1 - \exp[\left(\frac{t}{\alpha}\right)^{\beta}] \qquad [2\text{-}13]$$

where α is the scale parameter and β is the shape parameter of the distribution. The exponential distribution is a special case of the Weibull when β is equal to 1. The Weibull model accounts for degradation of performance as a function of time which is observed for most mechanical and structural components of a gate. Conversely, the exponential distribution is memoryless which implies that there is no deterioration in performance and that failure occurs at a constant rate throughout the lifetime of the components. This type of distribution is often applied to electrical components.

The probability of a given component being in the active or failed state while dormant may be determined using Markov analysis:

$$\frac{dP_{Active}}{dt} = -\lambda P_{Active}(t) \quad [2\text{-}14]$$

$$P_{Failed}(t) = 1 - P_{Active}(t) \quad [2\text{-}15]$$

where λ is a constant failure rate for the exponential distribution. A Markov model generally assumes constant rate of transition between its states which implies lack of deterioration and memorylessness of the systems. This however is not the case for all components of a gate. Mechanical and structural components experience degradation due to age and environmental conditions which is better represented with the Weibull model. To model degrading systems, the semi-Markov approach is used. This approach was first introduced in bridge deterioration modeling and uses the Weibull hazard rate function for rates of transition between deterioration states of the component (Ng, et al., 1998). To model mechanical systems which also experience deterioration, the constant λ in Equation 2-14 is replaced by the Weibull hazard rate function.

Modeling the availability of structural components is more complicated; they usually have longer life expectancies and require specific monitoring, testing and rehabilitation procedures. Similar to mechanical components, structural components also experience various degrees of deterioration during their life cycle and can be modeled by using the semi-Markov approach. Semi-Markov, multi-state Markov models have been used by researchers to model structural components in bridge monitoring and rehabilitation analysis (Sobanjo, 2011).

2.4.2 AVAILABILITY ANALYSIS

Availability is defined as the probability that a system performs as required at a specific point in time or over a period of time. This definition can be formulated as:

$$A = \frac{MTBR}{MTBR + MTTR}$$ [2-16]

where $MTBR$ is the "mean time between repairs" and $MTTR$ is the "Mean time to repair". Assuming idealized repairing conditions (system is restored to as good as new conditions after repair) the average availability of a dormant system with a dormancy period of *T,* reliability of *R(t)*, inspection time of t_1 and repair time of t_2 may be written (Ebelling 2007)

$$A(T) = \frac{\int_0^T R(T)dt}{T + t_1 + t_2[1 - R(T)]}$$ [2-17]

Using this equation, the average availability of a dormant system may be determined as a function of the dormancy period. Longer dormancy periods result in lower system availability; however, it is also economically unfeasible to have very frequent inspections (very short dormant periods). Cost optimization is required to obtain a balance between these parameters and to determine the optimum dormancy period for a given system.

2.5 REVIEW OF CURRENT RELIABILITY ANALYSIS SOFTWARE APPLICATIONS

Reliability analysis has a wide range of applications and many software programs have been developed that incorporate different reliability methods based on the type and condition of the system in question.

MechRel® (US Navy, 2011) has been developed by the Carderock Division of the Naval Surface Warfare Center to automate the use of their handbook of reliability prediction for mechanical equipment (CDNSWC, 2011). This software determines the failure rate of a component based on material properties, design parameters, and the intended operating environment. Failure rates can be calculated as a function of time at the level of a component, an assembly or system.

Isograph® is a company specialized in the development and supply of integrated Reliability, Availability, Maintainability and Safety software products. Reliability programs such as Fault Tree+®, Reliability Workbench® and Availability Workbench® are among the software applications developed by this company which feature reliability concepts such as Fault Tree analysis, failure rate prediction and reliability centered maintenance (Isograph, 1986).

ReliaSoft Corporation® is also a software development company in reliability engineering and related fields. Programs developed by ReliaSoft® include Weibull++®, λPREDICT®, and BlockSim® (ReliaSoft, 1992).

The University of California at Berkeley developed several reliability analysis softwares for teaching, research and engineering practice. Three of the most notable of these software applications are: CalREL®- a general purpose structural reliability analysis code written in FORTRAN, FERUM® (Finite-Element Reliability Using Matlab)- an open-source Matlab® toolbox designed for structural reliability analysis and OpenSees® (Open System for Earthquake Engineering Simulation)- an object-oriented code written in C++ for nonlinear structural response simulation (A. Der Kiureghian, 2006).

Below is a more detailed overview of two of the popular software applications mentioned above that can be used to assess spillway system reliability:

2.5.1 MECHREL®

A popular approach to estimate the reliability of components (specially mechanical and electrical equipment) is by the use of failure rates. Failure rates provide the basic understanding about the behavior of a component throughout its serviceable life. For a majority of components the failure rate is not constant and changes as a function of time. This function, which is referred to as the hazard function, assumes different shapes during different intervals of a components life cycle.

A bath-tube curve is the shape associated with the hazard function of a Weibull distribution. This U-shape curve demonstrates the variability of the rate of failure of a component in different stages of its life cycle. As shown in Figure 2-12, region A with an increasing rate of failure is known as the "break-in" period in which failures are mostly due to manufacturing defects. Region B is the "useful life" of the component wherein the failure rate is considered to be constant and finally, region C is the "wear-out" phase in which the component has degraded and it's nearing the end of its life.

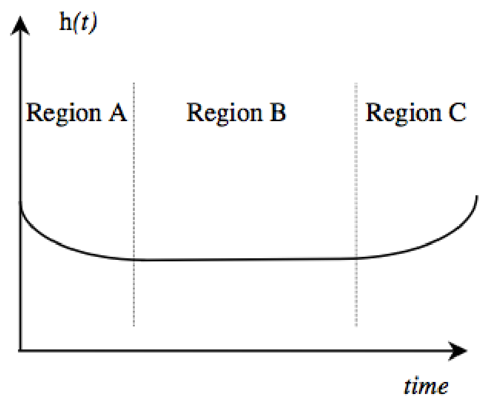

Figure 2-12: Bath-tube curve (USACE, 2001)

Failure rates are usually determined at the design stage of a component by the manufacturer. An issue with using failure rates in reliability analysis is the difficulty in estimating the failure rate of a component in service. A component in service is partly degraded and assigning a failure rate to such a component is challenging. Determining the failure rate of dormant components is compounded due to the fact that the true state of the component is not known and exposure to the environment increases the variability of the deterioration rate compared to similar components in an industrial setting.

Failure rate analysis of a complex system such as a spillway requires a comprehensive database containing data on failure rates of a wide variety of components (civil, mechanical and electrical). Such a database is not widely accessible in most industries. The Naval Surface Warfare Center (CDNSWC) has developed several products that can be used to project the reliability of a new design in its intended operating environment and determine occurrence probabilities of equipment failure modes such as wear and fatigue. The CDNSWC analysis procedure considers the design parameters, environmental extremes, and operating stresses as input parameters to determine the failure rate and hence the design life and reliability of a given component (CDSWC, 2010). Handbook of Reliability Prediction Procedures for Mechanical Equipment (CARDEROCKDIV, 2010) has detail instructions and information for determining the "actual" failure rate of a mechanical component using the parameters listed above. All the instructions and details have also been programmed into a software application called "MechRel®" in which one can define a project comprised of many systems and add predefined mechanical components to those systems. Each component based on its functions takes environmental, load and design information as input parameters and generates the "actual" failure rate as a result. After the failure rate of every component has been determined, the software automatically computes the failure rate of the entire system.

The sensitivity analysis of MechRel® determines the relationship between each input parameter and the failure rate of a component. For example Figure 2-13 illustrates the relationship between the operating temperature of the motor and its failure rate.

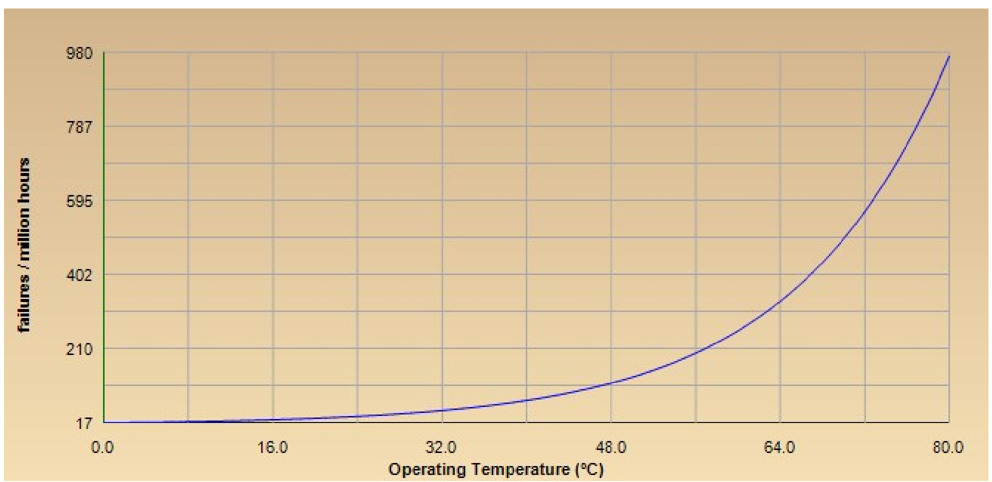

Figure 2-13: The relationship between the operating temperature and the failure rate of a motor (0-80 °C) (MechRel®)

This figure shows that operating temperature can have a major impact on the failure rate and should be monitored and controlled to ensure the failure rate remains in acceptable regions.

This software application is effective in estimating the actual failure rate of a component as it takes into account loading and design parameters as well as environmental conditions. The sensitivity analysis also identifies critical parameters and may be used as a guide in preparing the inspection/testing procedure for a component as it determines which parameter has the most influence on the failure rate. However, the predefined list of components in the software is limited to a few mechanical components and does not comprise many components typically present in spillway systems.

The Reliability Information Analysis Center (RIAC) of the US Department of Defense has also developed a database for non-electronic components called the Nonelectric Reliability Data Handbook (RIAC, 2011). The objective of this database is to catalog failure rate data for a wide variety of components. This handbook presents a list of components in alphabetical order with their relative failure rates. Each component has several failure rate bases on its usage (airborne, dormant, ground, naval and space flight).

2.5.2 RELIABILITY WORKBENCH®

The Reliability Workbench® suite developed by Isograph® includes state-of-the-art reliability tools such as FMECA and FMEA, Fault Tree Analysis, Reliability Block Diagram analysis, Reliability Allocation and Growth, Event Tree and Markov Analysis, and Weibull Analysis of historical failure data. Other helpful tools such as integrated parts libraries, extensive reporting tools, import and export facilities and enterprise class collaboration tools are also incorporated into the software application.

Reliability Workbench® allows users to develop projects using one or more of the integrated analysis modules. Each of the modules is an application in its own and can be used independently, but they can also be integrated and used in combination to build complex models. Some of the popular modules of this software application include:

1- The Prediction Module: a reliability prediction program which includes methods such as the electronic equipment reliability analysis described in MIL-HDBK-217 (U.S Department of Defense, 1991). This standard uses a series of models for various categories of electronic, electrical and electromechanical components to predict failure rates which are affected by environmental conditions, quality levels, stress conditions and various other parameters. The Prediction Module also provides mechanical equipment failure rates according to the NSWC Standard (Handbook of Reliability Prediction Procedures for Mechanical Equipment). As discussed in the previous section, this standard uses a series of models for various categories of mechanical components to predict failure rates which are affected by temperature, stresses, flow rates and various other parameters.

2- The FMECA Module of Reliability Workbench® provides the framework and reporting facilities to allow users to construct customized FMECAs. In addition, Process and Design FMEAs and commercial aircraft FMEAs may also be constructed and analyzed within this module. The FMECA Module automatically traces failure effects, severity values and failure causes through the system hierarchy. Failure rate and criticality values are automatically calculated by the program. The FMECA Module will also filter detectable and non-detectable failures in reports and determine the ratio between the frequency of detectable failures and total failures.

3- The Reliability Block Diagram (RBD) Module defines the logical interaction of failures within a system. This module is a systems reliability analysis tool that allows reliability block diagram analyses to be performed in an integrated environment. The RBD Module analyzes RBDs and produces the full minimal cut set representation for identified systems and sub-systems. It also calculates a range of importance measures as well as providing standard system and sub-system parameters such as unavailability, unreliability, number of expected failures etc. This module also includes a special Beta Factor Common Cause Failure (CCF) facility that allows users to associate groups of blocks with the same CCF model.

4- The Fault and Event Tree Modules of Reliability Workbench® provide interactive graphics and analysis capabilities for performing integrated fault tree and event tree analyses. The modules analyze fault and event trees producing the full minimal cut representation for fault tree top events and event tree consequences. The modules also include CCF, importance, uncertainty and sensitivity analyses.

5- The Markov Module of Reliability Workbench® analyses state transition diagrams using numerical integration techniques. The module can be used for defining multiple states representing continuous or discrete transitions. The program can also accommodate non-homogeneous processes by allowing time-dependent transition rates to be defined. Systems with time-dependent transition rates are strictly non-Markovian; however the addition of this facility in the program allows certain types of ageing processes to be modeled. The system logic is represented by a state transition diagram that may be constructed using interactive graphics. The system service life may be split into phases with different transition rates (Isograph, 2010).

2.6 OPTIMIZATION OF INPSECTION AND TESTING STRATEGIES

Inspection/tests may have varying levels of efficiency in assessing the state of components of the spillway gate system while the most efficient tests may have prohibitive costs. Therefore, an optimum inspection/testing strategy may be defined as a function of the efficiency and cost of inspection/tests and consequence of failure. Many studies have been conducted in this area; Kancev and Cepin (2011) investigate how costs and component aging affect the testing and maintenance optimization in terms of minimal system risk. Barroeta and Modarres (2005) study the optimal inspection policy for periodically tested, repairable components undergoing an aging process and Hontelez et al. (1996) develop optimum condition-based maintenance policies for deteriorating systems. To develop the optimum inspection/testing plan, it is essential to select the appropriate objective function to be optimized. Most methods minimize a cost function in order to obtain the optimum frequency of inspections/tests. In this approach it is important to take into account all costs such as costs of performing inspections/testing, cost of repair and consequences of failure (Ahmadi, et al., 2011) and (Vaurio, 1995).

Computational methods or algorithms for optimization fall into two classes: linear and nonlinear. Linear optimization normally involves constraints, and is referred to as linear programming when the constraints are linear. Nonlinear optimization can be constrained or unconstrained. Unconstrained optimization of a smooth function can be done using gradient and Hessian methods such as steepest descent or Newton-Raphson. Constrained optimization is often performed by applying a penalty to violation of the constraint (Davies, et al., 2006).

Constrained nonlinear programming problems often arise in many engineering applications. The most well-known optimization methods for solving these problems are sequential quadratic programming methods and generalized reduced gradient methods

(Yeniay, 2005). Although a number of methods are available for solving constrained nonlinear programming problems, there is no known method to determine the global minimum with certainty. The methods for constrained optimization can be divided into two categories as deterministic and stochastic methods. According to some comparative studies, the generalized reduced gradient (GRG) methods and the sequential quadratic programming (SQP) methods are two of the best deterministic local optimization methods (Kao, 1998). These gradient-based methods always look for the optimum closest to the starting point whether it is a local or global.

A number of softwares, such as Optima®, Matlab®, GRG®, and LSGRG®, are based on these widely used methods. In recent years, there has been an increasing interest to employ the stochastic methods, such as genetic algorithms (GA), simulated annealing (SA), and tabu search (TS) in solving complex optimization problems involving even non-differentiable, discontinuous, highly nonlinear objective, and constraint functions. These methods are stochastic global optimization methods which do not require gradient information unlike GRG and SQP. Below is an overview of two nonlinear optimization methods used in this study.

2.6.1 GENETIC ALGORITHM

Genetic algorithms (GAs) were invented by John Holland in the 1960s and were developed by Holland and his students and colleagues at the University of Michigan in the 1960s and the 1970s (Mitchell, 1999). GA is an optimization algorithm based on principles of evolution observed in nature. This approach imitates the evolution of living beings described by Darwin as survival of the fittest. The algorithm uses three main principles of the natural evolution: reproduction, natural selection and diversity of the species (Poppov, 2005).

Elements of a standard GA includes: populations of chromosomes, selection according to fitness, crossover to produce new offspring, and random mutation of new offspring. The Selection operator selects chromosomes in the population for reproduction. The fitter the chromosome, the more times it is likely to be selected to reproduce. The Crossover operator randomly chooses an element of a chromosome and exchanges the subsequences before and after that element between two chromosomes to create two offspring and the

Mutation operator randomly flips some of the bits in a chromosome.

A top level view of a basic genetic algorithm problem is as follows (Charbonneau, 2002):

- Randomly initialize population and evaluate fitness of its members
- Breed selected members of current population to produce offspring population selection based on fitness
- Replace current population by offspring population
- Evaluate fitness of new population members
- Repeat the above steps until the fittest member of the current population is deemed fit enough

To further elaborate, the first step when initializing a population is to first initiate chromosomes which are possible solutions to the optimization problem by encoding the randomly generated chromosomes into binary form. After the first population of chromosomes has been randomly created, the fitness of each chromosome is assessed using the fitness function based on the objective function of the optimization problem. Members are selected from the population for breeding with a probability of $P_{crossover}$. There are many methods for selecting members for breeding such as the Roulette Wheel or the Ranking Selection method (Mitchell, 1999). In all selection methods, the fittest members are more favored for breeding. During breeding, members are selected two at a time for crossover, in which the encoded strings are broken at a random location and the remaining sections of the string are exchanged to create two new offspring. New offspring are then mutated with a probability of $P_{mutation}$. During mutation, a random element of the binary encoded chromosome is selected and flipped to create an entirely new chromosome. This is repeated until all members of the population selected for breeding have generated new offspring. The new generation then replaces the old one and the process continues until the fitness criteria have been met.

Genetic Algorithms work by discovering, emphasizing, and recombining good "building blocks" of solutions in a highly parallel fashion. The idea here is that good solutions tend to be made up of good building block combinations of bit values that confer higher fitness on the strings in which they are present.

Holland (1975) introduced the notion of schemas to formalize the informal notion of "building blocks." A schema is a set of bit strings that can be described by a template made up of ones, zeros, and asterisks, the asterisks representing wild cards. For example, the schema $H = 1 * * * * 1$ represents the set of all 6−bit strings that begin and end with 1. The defined bits (non−asterisks) of a schema are known as its order and its defining length is the distance between its outermost defined bits (Mitchell, 1999).

At a given generation, while the GA is explicitly evaluating the fitness of the strings in the population, it is actually implicitly estimating the average fitness of a much larger number of schemas, where the average fitness of a schema is defined to be the average fitness of all possible instances of that schema.

Crossover and mutation can both destroy and create instances of a schema. However, the probability of survival under crossover is higher for shorter schemas. Also for mutation, the probability of survival of lower-order schemas is higher. This is known as the Schema Theorem (Holland, 1975). It describes the growth of a schema from one generation to the next. The Schema Theorem is often interpreted as implying that short, low-order schemas whose average fitness remains above the mean will receive exponentially increasing numbers of samples (i.e., instances evaluated) over time, since the number of samples of those schemas that are not disrupted and remain above average in fitness increases at each generation.

Crossover is believed to be a major source of the GA's power, with the ability to recombine instances of good schemas to form instances of equally good or better higher-order schemas while mutation prevents the loss of diversity at a given bit position. In evaluating a population of strings, the GA is implicitly estimating the average fitness of all schemas that are present in the population, and increasing or decreasing their representation according to the Schema Theorem (Mitchell, 1999).

2.6.2 CREEPING RANDOM SEARCH METHOD

The Random Search method consists of measuring the objective function of the optimization problem at random points selected from a probability distribution uniform over the entire parameter space and taking the smallest value as the minimum (Brooks, 1958). This requires a large number of trials which may be time consuming. An improvement to this approach is the Creeping Random Search method.

The creeping Random Search method generates random points in the first trial and starting from these base points, the objective function is measured at a predefined step size in a random direction. If the objective function at the new point has an improved value, the base point is moved to the new point. This is continued until moving a step size in any direction will not yield a smaller cost value (White, 1970).

This method while improved relative to the basic random search approach is still very time consuming relative to other optimization methods such as the Genetic Algorithm and is used in this study only as a comparative means to assess the level of accuracy of the results obtained from the Genetic Algorithm approach.

CHAPTER 3: MANUSCRIPT 1

APPLICATION OF DORMANT RELIABILITY ANALYSIS TO SPILLWAYS

Maryam Kalantarnia[1], Luc Chouinard[2], Stuart Foltz[3]

ABSTRACT

Dams are essential infrastructures for water supply, flood control, energy production and irrigation. A critical component for the safety of a dam is the spillway system which, by controlling releases, prevents overtopping of the dam. This in turn reduces impacts associated with excessive downstream flows and upstream water levels on infrastructures, the population and the environment. This article addresses reliability issues related to emergency spillways and specifically the estimation of their reliability level after prolonged periods of dormancy. During dormancy, spillway components are exposed to the environment and sustain cumulative damage that may trigger latent failures or failures on demand. Regular inspections and tests are used to detect and remediate latent failures and to assess the level of deterioration of components. The purpose of this study is to develop procedures to account for dormancy in the reliability analysis of spillways. It also demonstrates how these procedures can be used to evaluate the impact of the frequency of inspections and tests on the overall reliability of the spillways. This article introduces "Measure of performance", "Dormant availability analysis" and "Dormant availability analysis via integrity assessment" as methods to illustrate the unavailability/probability of failure on demand of a spillway system as a function of its dormancy period. This information can be used to determine the optimum frequency of inspection and tests taking into account the safety of the structure as well as the costs associated with inspection and testing.

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CE Database subject headings: Spillway, Gate, Reliability, Condition assessment, Availability, Component integrity.

3.1. INTRODUCTION

Spillway systems can perform several dam safety roles: control flows during floods, release excess flows during load rejections for run-of-the-river dams, regulate water levels for navigation or water supply, and lower reservoir water levels in the event of a deficiency in the structure or the foundation. Some spillways are routinely used in water management operations while others are used in rare occasions during floods. There is currently great interest in developing methodologies to estimate the reliability of spillways of the latter type as a function of potential operational and equipment failures. These spillways, like most safety systems, experience various degrees of dormancy (non-operation) throughout their service life. By definition, a system or subsystem is considered to be fully dormant if all of its components are in a non-operating state simultaneously and it is considered semi-dormant if only a subset of its components is non-operating at any particular time. The term dormancy is hereafter used to refer to both fully dormant and semi-dormant systems and subsystems. A dormant system is only activated on demand such that the dormant period is significantly longer than the active period. Regular inspections and testing are efficient means for monitoring the level of reliability of these systems and for identifying any needs in maintenance or part replacements to improve reliability.

The length of the dormancy period has a significant impact on the probability of failure on demand and risk, yet it is usually not considered in reliability and risk analyses for spillways. Typically, failure rates for dormant systems are lower than for active systems. However, since dormant periods are longer than active periods, failure during dormancy can be highly likely with severe consequences since latent failures occurring during dormancy are not identified until the system is re-activated in emergency situations.

The objective of this paper is to propose procedures to estimate the effect of dormancy on the reliability of a spillway. Factors that are considered are the length of the period of dormancy, the failure rate of the components of the system, their condition, and the system configuration. The models are used to demonstrate how the dormancy period can be reduced through periodic testing to meet a target reliability level for the spillway.

This paper is divided into two sections. The first section presents a review of the literature on risk assessment and reliability analysis for spillway gates, and introduces the notions of dormancy and availability for safety systems. The second section describes proposed methodologies to account for the effects of dormancy, testing and inspections on the reliability level of spillways. The proposed approach can be used to evaluate existing inspection and testing protocols or to design optimum inspection and testing strategies based on the reliability characteristics of each component and of the system. However, these aspects are beyond the scope of the current paper.

3.2. REVIEW OF THE LITERATURE

Numerous studies have been conducted over the past years to evaluate the safety of hydraulic structures. The National Research Council has recommended general approaches to estimate the probability distributions associated with extreme precipitation and runoff (NRC, 1988) while the ANCOLD guidelines provide detailed risk assessment approaches to ensure a high level of reliability for dam structures (ANCOLD, 2003). The Bureau of Reclamation also has proposed a comprehensive dam safety review program (USBR, 2012).

Lewin et al. (2003) review basic reliability principles for spillways as well as design philosophies for various types of facilities in Europe and America. Flood control facilities in America are often designed with large storage capacities which are characterized by long reaction times which allow for mitigation measures in the event of a failure on demand. Conversely, Europeans dams have smaller storage capacities and reaction times and dam safety issues must be addressed through redundancy of critical systems, and prescriptive testing and diagnostic procedures (Janssen, et al.1994).

Experience shows that spillway gate failure can be attributed to a wide range of equipment and operational failures. Typical target reliability levels that have been suggested correspond to 1 failure in 1000 demands for river control projects, and 1 in 10,000 demands for gate operations that may lead to dam failures (Lewin, et al., 2003).

Risk-based design validation models have been used to evaluate the level of safety of gates. For example, the "As Low As Reasonably Possible" (ALARP) criteria has been used in the design of gates (Bowles, 2004). Fault and event tree analyses have been used with mechanical and electrical components of spillways in order to determine their overall reliability (Barker, et al., 2006). Fault and event tree analyses have also been used for analyzing and comparing alternatives on staffing levels, choices on power back-up systems, and level of redundancy for spillway gates (Barker, et al., 2006; DEFRA, 2002; Berntsson, 2001). The input data required for these analyses are failure rates for each type of equipment which are typically obtained from compilations of failure data or from manufacturers for components that are in continuous use in a controlled environment. For components operating under different conditions, adjustment factors (i.e. K-factors) are used to modify the reference rates to account for dormancy and environmental exposure (Estes, et al., 2005). Failure rates of components in dormant state are usually smaller than failure rates when the components are active since they are not as highly solicited in the dormant state. However, since the dormant period may be much longer than the active period, failure may be more likely to occur while in the dormant state.

Another factor that influences the failure rates is the condition or state of components. K-factors can also be used to adjust failure rates as a function of the level of deterioration of a component. Failure rates reported in the literature generally do not account explicitly for the condition or state of a component, instead, the hazard function changes as a function of time to indicate increasing or decreasing failures rates as a function of the length of service life (USACE, 2006). The Weibull distribution is the most common model for representing increasing or decreasing hazard functions (or failure rates) as a function of time. The parameters of the distribution can also be modified as a function of time to model the various components of the traditional bathtub curve.

An alternative to the Weibull distribution is to use information on the current state or condition of a component in assigning a failure rate. Estes et al. 2005 propose the Condition Index (CI) as a basis for modifying the probability of failure of components to account for their current state. The CI is a numerical score that ranges from 100 (ideal condition) to 0 (failed condition) that is derived from quantitative or qualitative observations that correlates with the potential for failure. The condition tables associated with spillway gate components may be found in Appendix A. The uncertainty on the condition index is modeled as a random variable that is normally distributed. The probability of failure is obtained as the probability that the condition rating at time t (CI(t)) is lower than the condition rating that corresponds to failure ($CI_{failure}$).

$$P_f(t) = P[CI(t) \leq CI_{failure}] \quad [3\text{-}1]$$

The parameters (mean and standard deviation) of CI(t) are derived from component condition tables as a function of field observations obtained during inspections or tests. The mean parameter reflects the expected performance level of the component in a particular state while the standard deviation reflects uncertainties in component performance level and inspector assessments (Table 3-1). After each inspection, the reliability of the components may be calculated using the following Equation:

$$R(t) = 1 - P_f(t) = 1 - \varphi(-\beta) \text{ where } \beta = \frac{CI\,(t) - CI_{failure}}{\sqrt{\sigma^2 - \sigma_{failure}^2}} \quad [3\text{-}2]$$

Table 3-1: Condition index rating scale

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

3.3. PROPOSED METHODOLOGIES

The approaches discussed in the previous section have some shortcomings when applied to spillways. Equipment reliability analyses are often based on purely statistical approaches which require data on the historical performance of each type of equipment under similar operating and environmental conditions. Such data sets are often not available or incomplete for a variety of reasons. Equipment on older spillways is often custom built and performance data from similar equipment is usually not sufficient for statistical analysis. In addition, performance and maintenance records are often incomplete which may introduce bias in statistical analyses. In the case of spillways with standard equipment, reliability databases are usually relevant for manufacturing applications with minimal exposure to the environment and may not be directly applicable to spillways. Finally, many spillways are intended as emergency systems and are operated infrequently during periodic testing or emergencies and consequently spend most of their service life in a non-operating state. Failure to open the gate in the latter case may lead to overtopping of the dam and possible dam breach for embankment dams. In this section, an incremental procedure is used to develop a dormancy model that is applicable for the reliability analysis of a spillway gate system.

3.3.1. MEASURES OF PERFORMANCE

The two major events associated with the reliability of a system or components are failures and repairs and in consequence two basic measures of performance are the mean time to failure (MTTF) and the mean time between repairs (MTBR). The performance of a dormant system can also be evaluated by using other measures of performance such as PSSD (Probability of Successful Start-up on Demand), PSED (Probability of Start-up at the End of Dormancy) and PSF (Probability of Start-up Failure). For dam safety purposes, the most relevant is PSSD, which is described next.

Various models can be used to represent the reliability function R(t) of a component. One option is to use the exponential distribution for time to failure during dormancy. The assumption of exponentially distributed time to failure corresponds to a constant failure rate (λ_D) for the dormant system. For a system consisting of n independent components in series (i.e. a weakest link system), where λ_i is the active failure rate for component i and $K_i K_i$ is the K-factor for dormancy of component i, the dormant failure rate for the system is,

$$\lambda_D = \sum K_i . \lambda_i \quad [3\text{-}3]$$

The assumption of independence is conservative while the series system is reflective of the interactions between components of a spillway gate since only a small fraction of components are in parallel or standby (for example the emergency generator). Also, there is little load redistribution between elements and failure of a component will not significantly affect the failure of another. Furthermore, failure modes are not correlated and failure rates and the effect of environmental conditions on reliability vary from one component to the other.

For a dormant system there are two types of failures to consider: latent failure in the dormant state and failure at start-up during a test or inspection or during an emergency. In the first case, failure occurs prior to gate operation, while in the second case failure occurs due to the higher level of solicitation usually associated with start-up after a period of dormancy. Assuming that all components have the same dormancy period, the total number of start-ups during a period of time t for a system with dormancy periods of T is t/T. Therefore, the failure function (cumulative distribution function of time to failure) of a dormant system assuming an exponential distribution for time to failure may be written as:

$$F_{fail}(t) = 1 - \exp(-\lambda_D t)(PS_I)^{t/T} \quad [3\text{-}4]$$

where PS_I is the probability of successful start-up at the end of dormancy. Similarly the repair function (cumulative distribution function of time between repairs) of the system is:

$$F_{repair}(t) = 1 - [PS_I . \exp(-\lambda_D T)]^{t/T} \quad [3\text{-}5]$$

By definition the mean time to failure (MTTF) and mean time between repairs (MTBR) are:

$$MTTF = \int_0^{\infty} t dF_{fail}(t) \quad [3\text{-}6]$$

$$MTBR = \int_0^{\infty} t dF_{repair(t)} \quad [3\text{-}7]$$

Solving the above equations for the exponential case yields:

$$MTTF = \frac{1 - \exp(-\lambda_D T)}{\lambda_D [1 - PS_I . \exp(-\lambda_D T)]} \quad [3\text{-}8]$$

$$MTBR = \frac{T}{1 - PS_I . \exp(-\lambda_D T)} \quad [3\text{-}9]$$

The probability of the system to start on demand (PSSD) may then be calculated as:

$$PSSD = PS_I \frac{MTTF}{MTBR} = PS_I \frac{1 - \exp(-\lambda_D T)}{T \lambda_D} \quad [3\text{-}10]$$

The MTTF-to-MTBR ratio can be interpreted as the "availability" of the system to start. Multiplying by PS_1 yields the probability that the system will start for a random time selected from a uniform distribution. Note that this equation is only valid for systems which are fully dormant and neglects the time required to perform a test as well as the time to make a repair. If there is any active component within the system the model needs to be revised (Walsh 1996). The PSSD is a performance measure that characterizes the system for a given dormancy period T. This is equivalent to the average availability when the probability of successful start-up at the end of dormancy is equal to 1 and the time to perform tests and repairs are neglected.

3.3.2 DORMANT AVAILABILITY ANALYSIS

Availability can be defined as the probability that a system performs as required either at a specific point in time (point availability), or over a period of time (average availability). The average availability during a period of dormancy T is defined as the ratio between the uptime and the sum of the uptime and downtime during the period of time T.

$$A(T) = \frac{Uptime}{Uptime + Downtime} \quad [3\text{-}11]$$

Assuming idealized repairing conditions (the system is restored to "as good as new" conditions after repair), the average availability of a system with a dormant period T is equal to,

$$A(T) = \frac{\int_0^T R(t)dt}{T + t_1 + t_2[1 - R(T)]} \quad [3\text{-}12]$$

where *R(t)* is the reliability at time t, t_1 is the time required to perform an inspection or a test, and t_2 is the time required for a repair (Ebeling, 2007). Availability represents the proportion of time that the system is in a working state over the total time corresponding to the dormancy period plus the inspection and repair time in the event of a latent failure detected at the end of the dormancy period. Longer dormancy periods result in lower system availabilities due to the increase in the probability of a latent failure during dormancy. The average availaibility can also be obtained as the average of the point availability A(t) over a given period of time T,

$$A(T) = \frac{1}{T}\int_0^T A(t)dt \quad [3\text{-}13]$$

In the case when repair and testing times are neglected ($t_1 = t_2 = 0$), the point availability is equal to the reliability.

3.3.3 DORMANT AVAILABILITY ANALYSIS VIA INTEGRITY ASSESSMENT

Availability analysis can be enhanced by using integrity assessments for individual components. Integrity assessment is used to determine the level of deterioration occurring due to environmental exposure during the dormancy period.

This approach incorporates the dormant availability analysis and the condition indexing approach (Estes et al., 2005) discussed previously. While the Estes method of incorporating condition is effective in representing the deteriorating state of components after each inspection, it does not account for the dormant nature of the system. Note that in the Estes model, the state or condition of components is assumed to remain constant between inspections. In this approach, the condition of a component is obtained and updated from inspections at the beginning of each dormancy period and used to assign an appropriate failure rate for that period. This data is then used in the dormant availability analysis to model the state of the system under dormancy (in between inspections). After each inspection new data is obtained that determine if the system is either functioning as expected or deteriorating faster/slower than assumed. By integrating this data the model can represent the state of the system more accurately.

To account for deterioration during dormancy, a Weibull distribution is used for the time-varying reliability of the system (or time-varying probability of failure):

$$R(t) = 1 - P_f[CI(t)] = exp\left[-(\frac{t}{\alpha})^{\theta}\right] \quad [3\text{-}14]$$

where α is the scale parameter or characteristic life of the component and θ is the shape parameter (USACE, 2006). The parameter θ can be determined from databases as a function of the failure mode of the component (USACE, 2006). Note that the exponential distribution (constant failure rate) is a special case of the Weibull distribution (θ=1). Given P_f and θ, α is calculated directly as:

$$\alpha = \frac{t}{\left[-\ln\left(1 - P_f\right)\right]^{1/\theta}} \quad [3\text{-}15]$$

where P_f is the failure probability associated with the condition of the component (CI) as defined in Equation [3-2]. Assuming negligible inspection and repair times compared to the dormancy period ($t_1 = t_2 = 0$), the average availability of the dormant system may be calculated as:

$$A(T) = \frac{1}{T}\int_0^T A(t)dt = \frac{\int_0^T exp\left[-\left(\frac{t}{\alpha}\right)^{\theta}\right]dt}{T} \quad [3\text{-}16]$$

In the dormant availability model θ remains constant while α changes as a function of the condition index after each inspection.

The representation of spillway gates as a series system and the assumption of independence for the failure modes of components are also applied to the updated model. Note that the degree of degradation of components as measured by the condition or state index is independently determined for each component.

3.4. CASE STUDY I: RELIABILITY OF A TAINTER GATE USING MEASURE OF PERFORMANCE AND DORMANT AVAILABILITY ANALYSIS

The first case study is based on a model for the reliability of a Tainter gate developed by the USACE (Schultz, 2009). The system for the Tainter gate includes the mechanical, electrical, and operational components listed in Table 3-2 with the corresponding failure rates. It is assumed that the reliability function of each component/event follows an exponential distribution and all components are in series and independent (with the exception of commercial and emergency power in electrical power which are in parallel). For demonstration purposes, it is assumed that the probability of successful start-up (PS_1) at the end of dormancy (during inspections/tests) is equal to 0.96 and that tests are fully efficient in detecting latent failures. In practice, this value should be determined from statistics obtained from regularly scheduled tests or unplanned operations. This emphasizes the need to develop procedures to perform tests on a regular basis and to document outcomes from tests as well as from unplanned operations.

Table 3-2: Tainter gate system components

Components	**Yearly Failure Rate**	**Components**	**Yearly Failure Rate**
Mechanical System - Right side drive		**Mechanical System - Left side drive**	
Coupling between motor and gear box	0.0200	Shaft couplings	0.0200
Right angle gear box	0.0295	Connecting shaft	0.0140
Coupling between right angle drive gears and primary gear reducer (Coupling T1B66)	0.0200	Primary spur gear	0.0187
Connecting shaft	0.0140	Gear on sheave	0.0187
Coupling between right angle drive gears and primary gear reducer (Coupling T1B67)	0.0200	Wire rope sheave	0.0339
Parallel gears (Gear box)	0.0280	Left side wire ropes	0.0560
Primary spur gear	0.0187	Connecting shaft support roller bearings 1	0.0280
Gear on sheave	0.0187	Connecting shaft support roller bearings 2	0.0280
Wire rope sheave	0.0339	Connecting shaft support roller bearings 3	0.0280
Brake	0.0249	**Electrical System Components**	
Right side wire ropes	0.0560	Electric motor	0.0147
Sheave roller bearing right side	0.0280	Electric motor starter	0.0159
Sheave roller bearing left side	0.0280	Power to release brake	0.0159
Electric power cable to motor	0.0125	**Operational System Events**	
Electrical Power		Gate operation delivery to field of ice	0.02
Manual transfer switch	0.0154	Operator accessibility to site/storm	0.05
Commercial power		Operator experience with controls	0.04

External power	0.0200	Vandalism	0.02
Main circuit breaker	0.0159	**Control system failure events**	
Underground cables	0.0167	Power cable to motor starter	0.0125
Emergency power		Manual push button control switch	0.0159
Standby generator	0.0200	**Gate jamming events**	
Service disconnect switch	0.0128	Ice freezes between wall and gate	0.01
Cables in duct tray	0.0125	Floating debris wedges between gate and wall	0.01

Figure 3-1 illustrates the availability of each mechanical component for dormant periods ranging from 1 month to 2 years. In the analysis, it is assumed that all components are inspected / tested with the same frequency and do not deteriorate as a function of time. Note that in practice, the frequency of inspections can vary for different types of components as a function of the failure rate. Similar results are obtained for civil, electrical and operational components. Availability analysis of individual components shows that mechanical and operational systems are the most sensitive systems to the dormancy period as they have the largest failure rates.

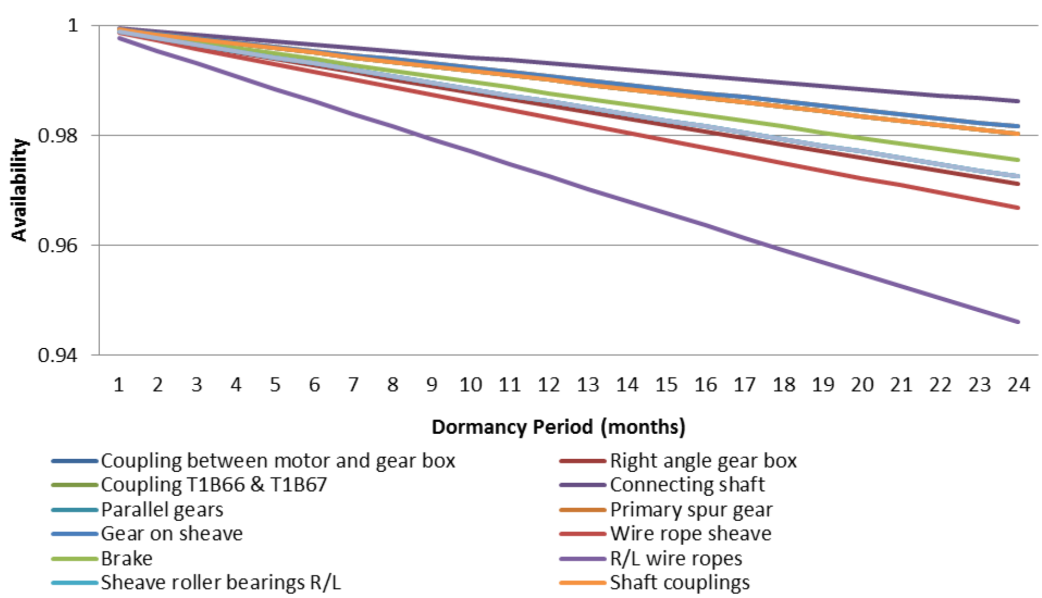


Figure 3-1: Availability of mechanical system components

Figure 3-2 shows the PSSD for the mechanical system components and Figure 3-3 the PSSD of the Tainter gate system as a whole and its subsystems over a dormancy period of up to 5 years.

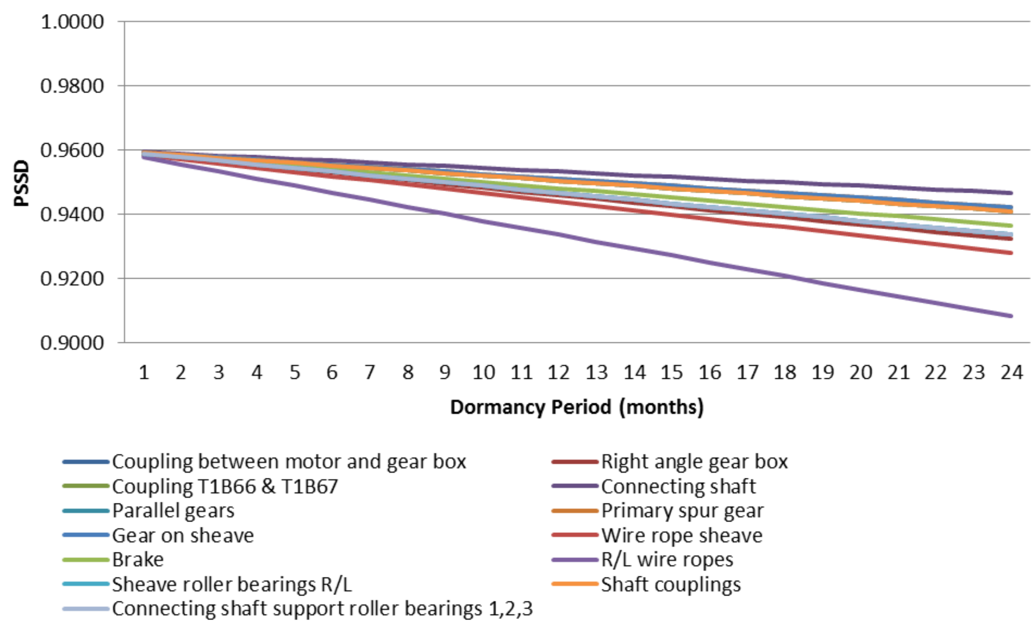


Figure 3-2: PSSD of mechanical system components

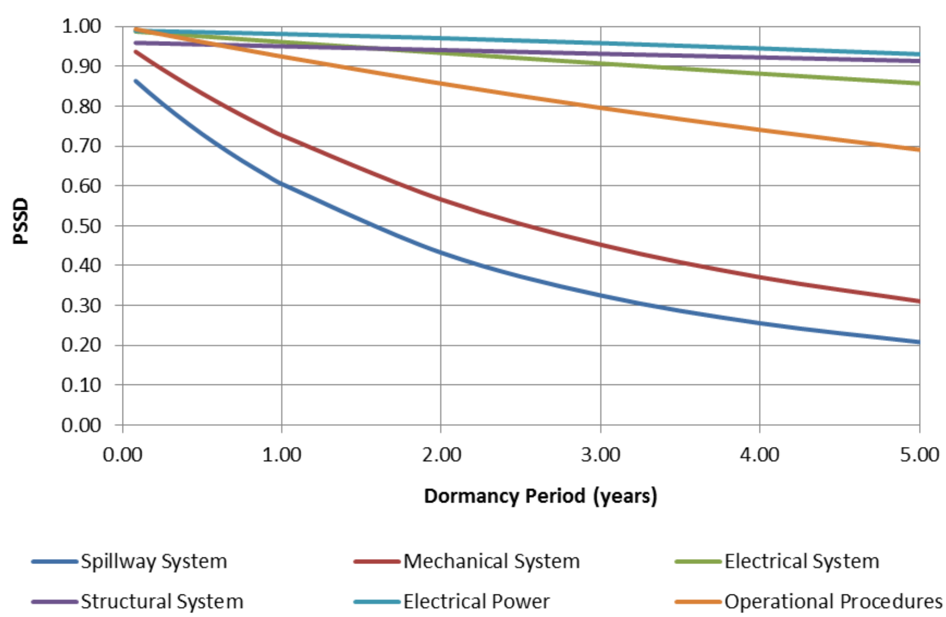


Figure 3-3: PSSD for tainter gate system

It may be observed from Figure 3-3 that PSSD decreases significantly with the length of dormancy. These probabilities can be used in risk analysis of the spillway to determine the maximum length of the dormancy period or to optimize the frequency of tests and inspections.

Although the Measure of Performance and Dormant Availability Analysis methods account for the effect of dormancy on system reliability, their application to specific facilities can be limited due to lack of data on failure rates for components and poorly documented inspection and periodic test results. The next case study demonstrates how the Dormant Availability Analysis based on the Integrity Assessment Approach can be used as an alternative to resolve these issues.

3.5. CASE STUDY II: RELIABILITY OF A VERTICAL LIFT GATE USING DORMANT AVAILABILITY ANALYSIS VIA INTEGRITY ASSESSMENT

The second case study is applied to a vertical lift gate. A vertical lift gate consists of a metal plate which slides up and down in two slots assisted by wheels or rollers. For the purpose of the case study, the design service life for all components is assumed to be 50 years. The spillway is only used for emergency situations during large floods; therefore all components spend most of their service life in a dormant state and are activated only during floods or for periodic tests.

Inspection results at the initial start-up of the spillway are assumed to be those shown in Table 3-3. A more detailed list of components and condition index values may be found in Appendix B. Scheduled inspections and tests of the gate system are performed once every 5 years during which the inspector makes an observation on the state of components and assigns a condition state.

Table 3-3: Condition state of spillway components at the initial start-up of the spillway

System Indicators	Condition State	Condition Index	
		Max	Min
Gathering Information	7	100	85
Decision Process	6	84	70
Access and Operations	7	100	85

System Indicators	Condition State	Condition Index	
		Max	Min
Power Supply	7	100	85
Cables and Controls	7	100	85
Supporting Structure	7	100	85
Gate Structure and Support	7	100	85
Access and Control	7	100	85
Power Supply and Controls	7	100	85
Force Transmission	7	100	85

Using Equation [3-2] and the data from Table 3-3, the failure probability of the spillway and of the subsystems are determined over the service life of 50 years (Figure 3-4).

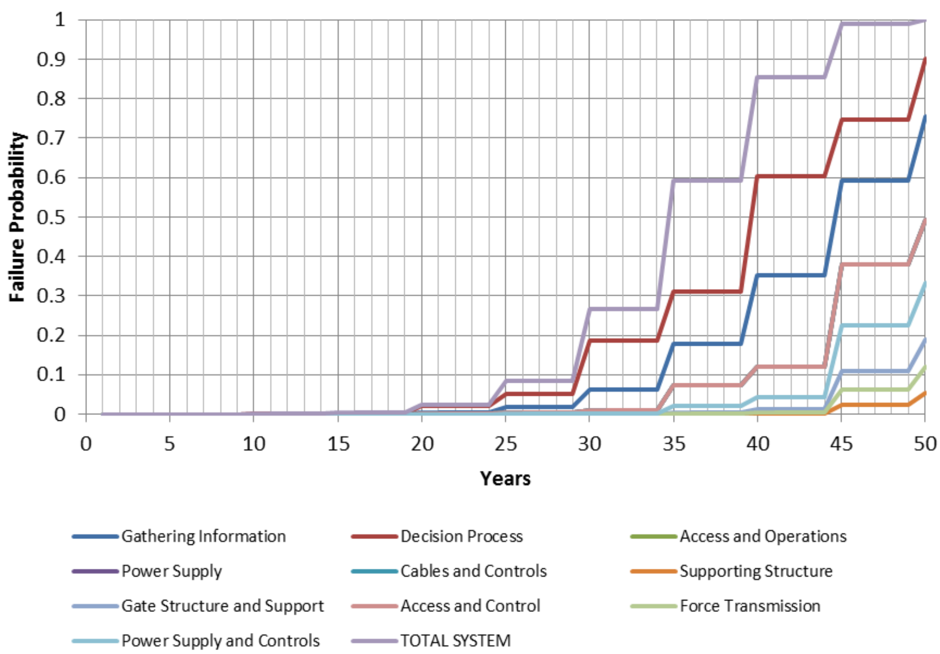


Figure 3-4: Failure probability of the spillway system using the integrity assessment approach

In this case study, the condition of each subsystem is assumed to degrade linearly in time at different rates since subsystems may be exposed to varying degrees to the environment or exhibit different degrees of resiliency to exposure.

The second step in this case study is to apply the dormant availability analysis to the deteriorating system. Figure 3-5 shows the results of the dormant availability analysis using integrity assessment for the vertical gate system. The results are shown as point unavailability of both the sub-systems and the total system during the 50 years life cycle. Average unavailability of the total system is shown as values at the mid-point of each dormancy period. Also shown on the figure is the probability of safe start-up on demand (PSSD).

At each inspection, observations on the state (CI) of components are obtained and used to update the parameter α of the dormant availability model. Also, since the system is tested at each inspection the unavailability returns to zero as there is either no failure or the component had failed and is repaired.

Point unavailability corresponds to the probability of failure on demand at any point in time during the service life of the system while the average unavailability shows the average for each dormancy period. Finally the parameter PSSD is a function of the period of dormancy of the system and since this period is assumed constant and identical for all components it remains constant for the entire period.

This approach is well adapted to the current state of practice for spillway gates since it accounts for the dormant state of components and is not dependent on data bases for failure rates of components. The framework is immediately workable and can be improved as data is collected to validate and/or adjust the reliability model.

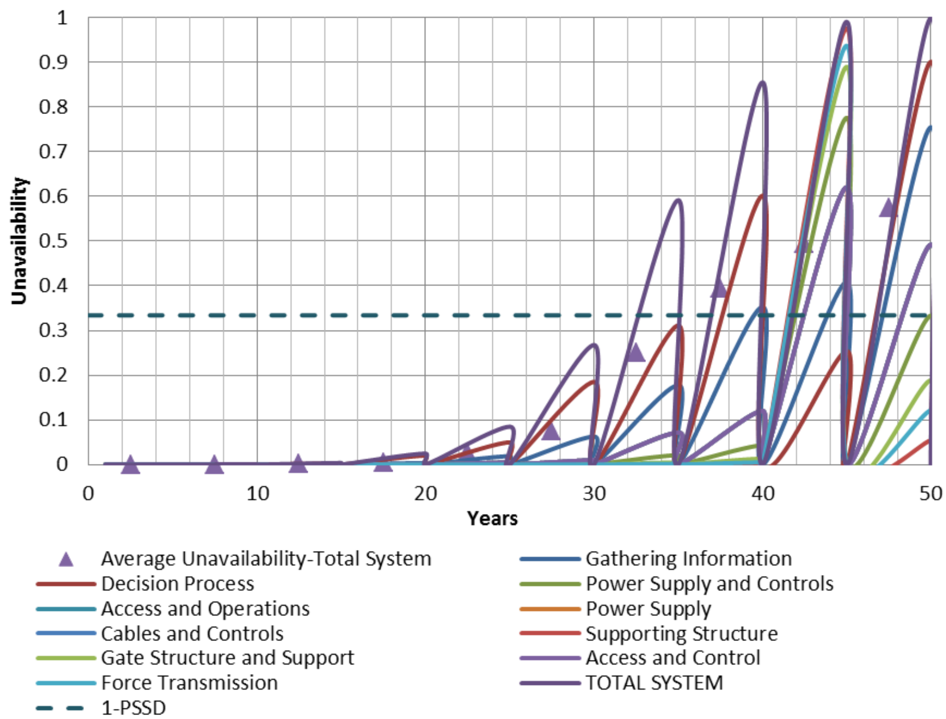


Figure 3-5: Results of the dormant availability analysis using the integrity assessment approach

3.6 CONCLUSION

Spillways are critical components for the safe operation of a dam and estimating their level of reliability is an important input to dam safety programs. This estimation is a challenging task given the nature of spillways. Spillways are complex systems made up of a mixture of interrelated subsystems (civil, mechanical, electrical and operational), and many spillways are used infrequently and remain in a dormant state during most of their service life. This paper has reviewed existing techniques of reliability and risk assessment of spillway gates that address system reliability and proposes methods to account for dormancy of the system. The results are models that evaluate the availability of a spillway as a function of time based on inspection and testing.

The first model (measure of performance) can be used to characterize the overall performance of the system. Characteristics such as the probability of failure on demand of a spillway gate may be vital in the event of a flood or load rejection. Limitations of this approach include lack of statistical failure data and the inability to model deterioration (the use exponential distribution in the model). The second model (dormant availability analysis) shows the availability of a system as a function of its dormancy period. This model is more flexible as it can support other probability distribution functions such as Weibull which can model system deterioration. However, this approach also has the limitation of lack of data.

Lack of statistical data on failure of components makes it difficult to apply traditional reliability analysis procedures to spillways. The integrity assessment model has been presented as a tool to quantify the condition of the system and translate this information into failure data. This model can account for the deterioration of components and be updated using data from inspections and condition assessments. Since latent failures occurring in dormant periods are revealed during an emergency or during planned tests, the model can be used to select the frequency of tests as a function of the desired level of reliability. The newly proposed "dormant availability using integrity assessment" model has the advantage of accounting for the dormancy of a system while allowing continuous updating based on inspections and operational incidents.

Constraints and limitations in this approach include calibration of the model in its early stages of application. This might be difficult to conduct due to the lack of validated quantitative data; however, as more information is gathered on the system during inspection/testing periods, the model will be updated and therefore become more and more accurate.

The model can also be used to determine optimal inspection and testing schedules to achieve the highest level of reliability at the lowest cost. This may be done by optimizing the risk function using system unavailability and costs associated with inspection/testing and consequences of failure. This topic however is not within the scopes of this paper and is considered a paper by itself which will be developed in the future.

CHAPTER 4: MANUSCRIPT 2

AVAILABILITY ANALYSIS SOFTWARE APPLICATION FOR SPILLWAY GATE SYSTEMS

Maryam Kalantarnia, Luc Chouinard, Stuart Foltz

ABSTRACT

Determining the availability of a spillway gate system is crucial for the dam industry and public safety. Failure to operate the gates on demand (during high flow or load rejection) can lead to dam overtopping and major downstream consequences. Due to the exposure of spillways to severe environmental conditions and to the long periods of dormancy of most spillways and the complexity of modelling interactions of electrical, mechanical and civil subsystems, it is often difficult to perform reliability analysis on spillway gate systems.

This paper introduces a software application developed specifically for the reliability analysis of such systems. This software application uses object-oriented programming and provides a user-friendly interface to model complex systems, and to include inspection, tests and component replacement options. The software determines the availability of the system as a function of the length of the service life and identifies the optimum inspection and testing strategy based on user-set unavailability limits and a benefit-cost analysis. Reliability analysis methods featured by this software include Markov/semi-Markov analysis, Fault Tree analysis and optimization techniques based on the Random Search Method (RSM) and Genetic Algorithms (GA). This paper describes the objectives, architecture, features and methods of analysis employed in this software.

KEYWORDS: Object-oriented programming, software application, Reliability software, Availability analysis, Optimization.

4.1 INTRODUCTION

Reliability analysis has a wide range of applications and many software programs have been developed which incorporate different reliability methods adapted to the type and conditions of operation of the system in question. For example, the MechRel® software (US Navy, 2011) has been developed by the Carderock Division of the Naval Surface Warfare Center to automate the use of their handbook of reliability prediction for mechanical equipment (CDNSWC, 2011). This software determines the failure rate of a component based on material properties, design parameters, and the intended operating environment. Failure rates can be calculated as a function of time at the component, assembly and system levels. Isograph® developed several reliability programs such as Fault Tree+®, Reliability Workbench® and Availability Workbench® that feature reliability concepts such as Fault Tree analysis, failure rate prediction and reliability centered maintenance (Isograph, 1986). ReliaSoft Corporation® is also a software development company in reliability engineering and related fields. Programs developed by ReliaSoft® include Weibull++, $\lambda^{PREDICT}$, and BlockSim (ReliaSoft, 1992). Efforts have also been made at the University of California at Berkeley to develop reliability analysis software for teaching, research and engineering practice services. Three of the most notable of these software applications are: CalREL®- a general purpose structural reliability analysis code, FERUM® (Finite-Element Reliability Using Matlab)- an open-source Matlab® toolbox designed for structural reliability analysis and OpenSees® (Open System for Earthquake Engineering Simulation)- an object-oriented code written in C++ for nonlinear structural response simulation (A. Der Kiureghian, 2006).

Although many programs are available that incorporate a variety of different reliability methods, most cannot be used to accurately determine the reliability of spillway gate systems. Spillway gates are complex systems comprised of electrical, mechanical and structural components exposed to extreme environmental conditions. The dormant nature of spillway gates also adds to the complexity of the system. Therefore, it cannot be modeled using traditional reliability methods incorporated in existing software.

Numerous studies have been conducted over the past years to develop methodologies to accurately determine the reliability of spillways. The National Research Council has recommended general approaches to estimate the probability distributions associated with extreme precipitation and runoff (NRC, 1988) while ANCOLD guidelines provide detailed risk assessment approaches to ensure a high level of reliability for dam structures (ANCOLD, 2003). These approaches can be used to evaluate the capacity and adequacy of spillway systems as a function of the anticipated demands for the timely evacuation of excess flows.

In addition, spillways are key elements for the operational safety of dams and improvement in the reliability of existing gates through inspection, testing, maintenance and repair is a topic of great importance. The type and frequency of inspections/tests of spillway gate facilities used to assess the performance level of various components represent a major commitment of financial resources and personnel for dam owners. The Federal Emergency Management Agency (FEMA, 2012) and the United States Society on Dams (USSD, 2002) present a thorough overview of spillway gate systems and review industry guidelines for the evaluation of maintenance, inspection and testing procedures of spillway gate component. These activities and the information that is collected in this process should be considered when evaluating the in-service reliability of the spillway gates. Estes and Foltz (2006) propose an approach to estimate the reliability of a system using condition assessments derived from inspections and tests which was extended by Chouinard, et al. (2008) and Kalantarnia, et al. (2011) to include dormancy effects associated with testing and inspections.

The objective of this paper is to introduce a software application specifically designed for reliability analysis of spillway gate systems. This software application is developed in Visual Basic® using object-oriented programming. This software has a strong user interface from which the user is able to model complex systems, add inspection, tests and component replacement options to the system, determine the availability of the system as a function of service life and identify the optimum inspection and testing period based on unavailability limits and costs of inspections/tests vs. consequence of failure. Reliability analysis methods featured by this software include Markov/semi-Markov analysis, Fault Tree analysis and optimization techniques such as Random Search method and Genetic algorithm.

This article aims to describe the objectives, architecture, features and methods of analysis employed in this software. The second section introduces the software application by describing its objectives, architecture and interface, the third section gives a general overview on the techniques and methodologies used in system modeling and availability analysis, and finally section four is a case study demonstrating the abilities of the software.

4.2 INTRODUCTION TO THE SOFTWARE APPLICATION

As discussed, spillway gates are complicated systems with customized components undergoing long periods of dormancy under severe environmental conditions. These circumstances make it very difficult to accurately determine the reliability of such systems. Therefore, it is the objective of this software application to model the reliability of a spillway gate system on demand (systems availability) considering component type, dormancy period, environmental conditions and inspection and testing strategies. This software application is an object-oriented code written in Visual Basic with a strong interface which enables the user to navigate easily through related menus and dialog boxes in order to model and analyze a given system. Figure 4-1 shows the main page consisting of a project tree control which allows the user to develop the fault tree model of a system using *Add Project*, *Event* and *Component* options from the top menu. Three tabs on the right of the project tree control are used to review and evaluate a model; the *Summary tab* provides the name and description of events or components added to the fault tree by the user. The *Chart* and *Table* tabs show the unavailability diagram and values of any selected event or component respectively as a result of the analysis.

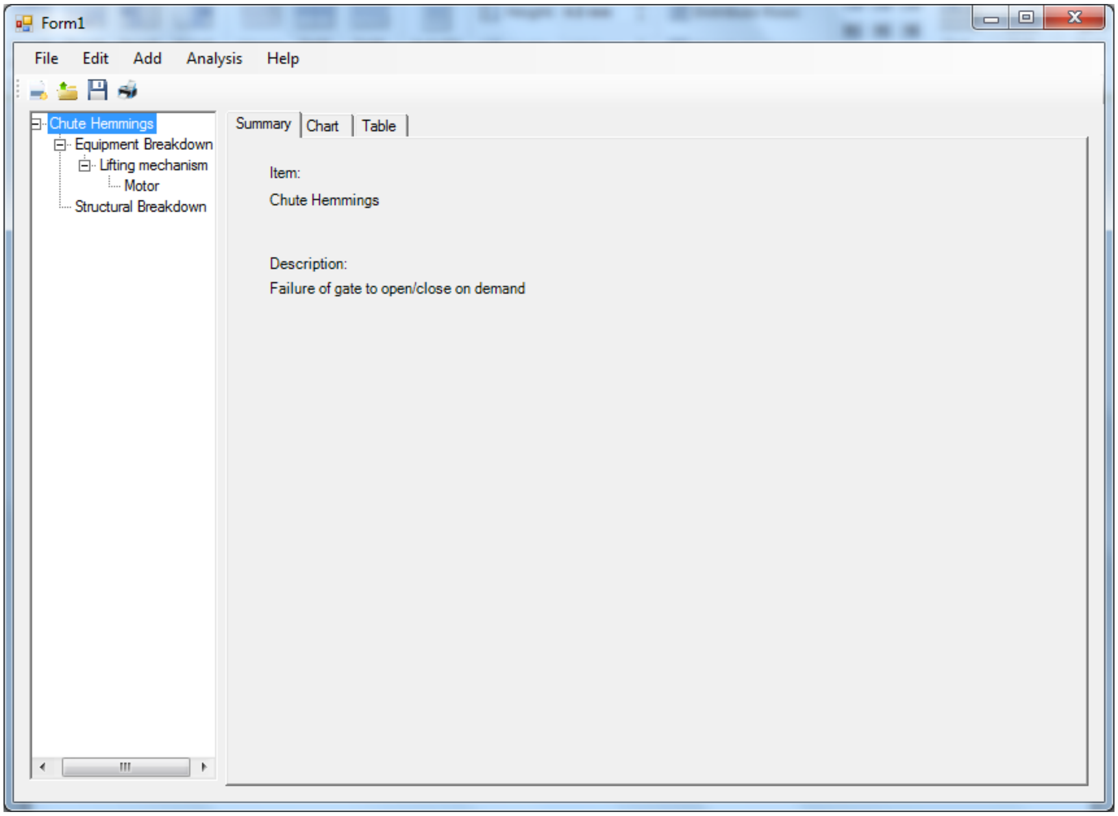


Figure 4-1: Main page of the software application

The first step in modeling a spillways gate system is to define a project and create a fault tree with the top event defined as gate failure and build the tree from the top to the basic events which correspond to the failure of gate components. Intermediate events can be added to the tree by the *Add Event* option while the basic events are created using the *Add Component* option. The initial choice of component is between electrical/mechanical component and structural component. The necessity of differentiating between these two types of components is explained in the following section. The *New Component* dialog box contains options for defining failure distribution parameters, the type, frequency and efficiency of inspection/tests conducted on the component, replacement options, environmental exposure conditions and duty cycle factor (operating time/total time) corresponding to the dormancy of the component. When creating events or components, the user has the option of choosing between *AND* and *OR* gates within the fault tree based on the interactions between the tree elements.

The user can also add inspections/tests using the *Add Inspection/Test* option in the *Add* menu. Inspections/tests performed on the system can be added and defined by specifying the frequency and efficiency. Once the fault tree has been created and all parameters and inspection and test types and frequencies have been added, the software application can determine the unavailability of each component, subsystem and the spillway gate system as a function time throughout its service life. The results of the analysis are displayed as both unavailability diagrams and values. Also, the application provides unavailability histograms and average unavailability of any selected item of the fault tree as well as the minimum cut sets of the fault tree. A minimal cut set is the shortest path from a basic event in the fault tree to the top event constituting a critical failure path (Ebeling, 1997).

This software application also has the option to perform optimization analysis and identify the optimal inspection and testing periods based on unavailability limits and costs of inspections/tests vs. consequence of failure. Details of the techniques used in this approach are beyond the scope of this paper.

4.3 METHODOLOGIES USED IN SYSTEM MODELING

4.3.1 FAULT TREE ANALYSIS

A Fault tree analysis is a deductive graphical design technique which is structured in terms of events and identifies ways in which basic causes of failure may lead the failure of a system. This diagram uses logic gates to express logical relationships between events. The most common gates used in a fault tree are AND and OR gates. Basic AND gates require that all connected events combine to yield the top event; however, in the case of the OR gate, occurrence of at least one event is sufficient to lead to the top event. As discussed previously the software applications allows users to create a fault tree of the spillway gate system by generating events and components and their interactions. The basic events of the fault tree, which represent the root causes of the top event, are component failures, represented by failure distribution parameters, which the user can create using the *Add Component* option.

Once all the basic events are identified and the failure parameters of the components are known, the unavailability of the spillway gate system is determined by applying Boolean algebra for each branch of the tree from the bottom to the top.

4.3.2 MARKOV/SEMI-MARKOV ANALYSIS

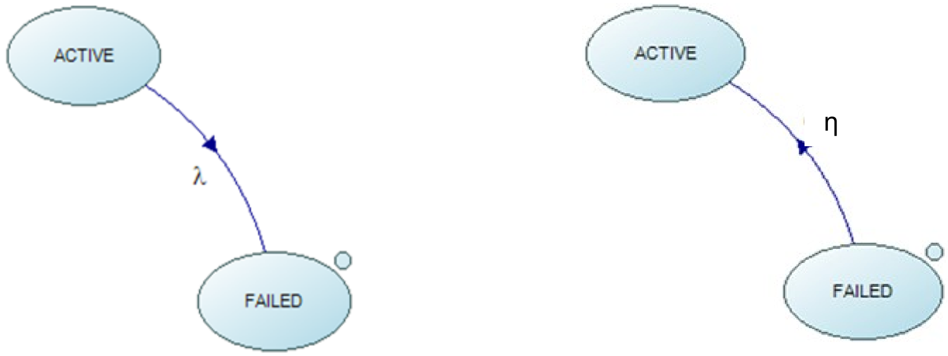
Components of most spillway gate systems spend the majority of their service life in a dormant state and are activated randomly (i.e. for flood flows or load rejection) or on a regular basis for inspection and testing. Also most spillways are located in remote areas and are subjected to severe environmental conditions which can cause degradation of components or a decrease in performance level. Therefore, to determine the availability of spillway gate components, an approach needs to be selected which can account for both the effect of dormancy and environmental conditions.

Markov analysis is a reliability modeling approach used for systems which move from one state to another (Ebeling, 1997). Therefore Markov analysis is capable of modeling dormant systems in which a functional component can fail whithout detection (latent failure). This type of failure can only be detected if the system is activated. To model the components of a spillway gate system using Markov analysis, the model must show the component moving from active to failed states and vise-versa. This section descibes the Markov models used in the software application to determine component unavaialbility.

4.3.2.1 ELECTIRCAL/MECHANICAL COMPONENTS

To model electrical/mechanical components, the software application considers two states: 1) fully operational (active state) and 2) state of latent failure (failed state). Figure 4-2 illustrates the Markov model for a component of the spillway gate system.

For simplicity, it is assumed that the components are active at the beginning of their service life and that only latent failures occur. In other words, failures occur during dormancy and not during the actual gate operation.



(a) (b)

Figure 4-2: Markov model (a) transition from active to failed state during dormancy, (b) transition from failed to active state during inspection/testing

In this figure, λ represents the rate of transfer from active to failed state during dormancy, or in other words the latent failure rate, and η represents the rate of transfer from failed to active state when a failed component is detected and either replaced or repaired.

The Weibull and exponential distributions can be used to model the time to failure of the components. The cumulative distribution function of time to failure for the Weibull function is:

$$F(t) = 1 - \exp[\left(\frac{t}{\alpha}\right)^{\beta}] \quad [4\text{-}1]$$

where α is the scale parameter and β is the shape parameter of the distribution. The exponential distribution is a special case of the Weibull when β is equal to 1. The Weibull model accounts for degradation of performance as a function of time which is observed for most mechanical and structural components of a gate. Conversely, the exponential distribution is memoryless which implies that there is no deterioration in performance and that failure occurs at a constant rate throughout the lifetime of the components. This type of distribution is often applied to electrical components. Hence, in Figure 4-2(a), λ represents the failure rate of either a Weibull or an exponential distribution depending on the type of component. Figure 4-3 shows the "New Component" dialog box where the user can choose between exponential and Weibull distributions and add their respective parameters in the areas provided.

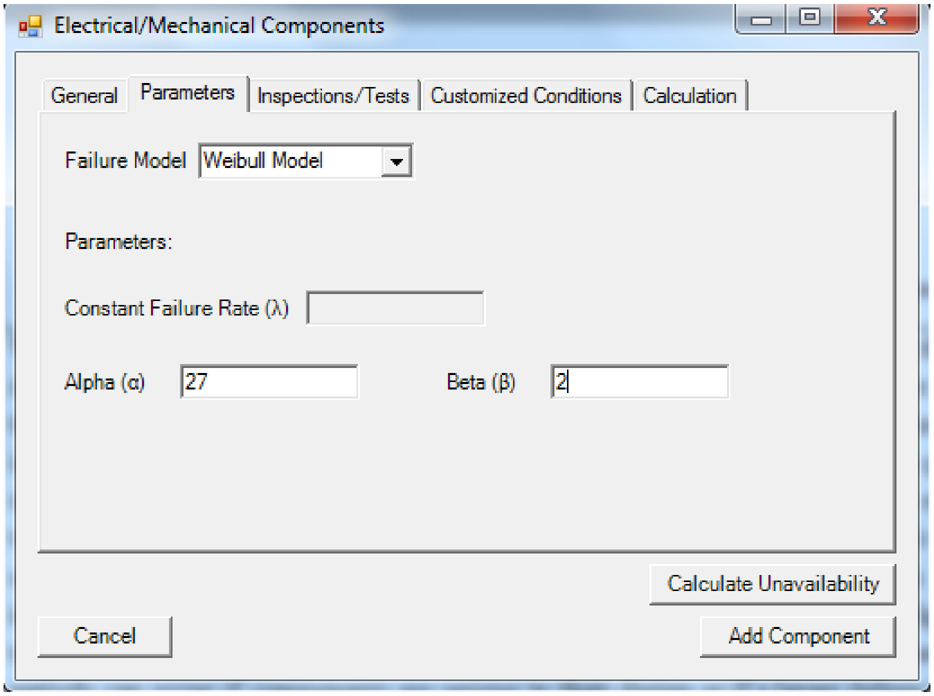


Figure 4-3: New component dialog box for electrical/mechanical components, parameters tab

When components are inspected or tested after each dormancy period, the probability of detecting a failure depends on the type of inspection/test performed. In Figure 4-2(b), η represents the efficiency of the inspection/test in detecting failure. In this study it is assumed that if a failure is detected it is immediately restored to the same condition prior to failure (as good as old). This simplifying assumption is used to focus the objective of the analysis on the effect of testing/inspection on the reliability of a deteriorating system and corresponds to the worst case scenario. Also, since in most spillways the dormancy period is much larger than the inspection/testing period, inspection time and repair time are considered negligible with respect to the dormancy period. This assumption is used for demonstration purposes but long repair periods can occur if components are unique in their design or if a latent failure is associated with major structural components.

The probability of a given component being in the active or failed state while dormant (as shown in Figure 4-2(a) may be determined using Markov analysis shown in Equations 4-2 and 4-3.

$$\frac{dP_{Active}}{dt} = -\lambda P_{Active}(t) \quad [4\text{-}2]$$

$$P_{Failed}(t) = 1 - P_{Active}(t) \tag{4-3}$$

where λ is a constant failure rate for the exponential distribution. A Markov model generally assumes constant rate of transition between its states which implies lack of deterioration and lack of memory of the system. However, this is not the case for all components of a gate. Mechanical and structural components experience degradation due to age and environmental conditions which is better represented with the Weibull model. To model degrading systems, the semi-Markov approach is used. This approach was first introduced in bridge deterioration modeling and uses the Weibull hazard rate function as transition rates between deteriorating states of the component (Ng, et al., 1998). To model mechanical systems which also experience deterioration, the software application also uses the semi-Markov approach by replacing the constant λ in Equation 4-2 by Equation 4-4 shown below:

$$\lambda = \beta \frac{t^{\beta-1}}{\alpha^{\beta}} \tag{4-4}$$

When the system undergoes inspection/tests [Figure 4-2(b)], if the component is operable (active state) it remains in the same state; however, if it is in the failed state and the failure is detected, it is assumed that it will instantaneously be repaired to its condition prior to failure (as good as old) as shown in Equation 4-5.

$$P_{Active}(n) = P_{Active}(n-1) + \eta \times P_{Failed}(n-1) \tag{4-5}$$

where η is probability of detection of failures which is a function of the type of test conducted. The user also has the option of component replacement in which after a specific unavailability limit determined by the user is surpassed, the component will automatically be replaced with a new one at the next inspection/test cycle.

To customize the hazard rate function, K-factors have been added to the model to account for environmental exposure conditions of the component. Also a duty cycle factor has been added to update the hazard rate function based on the dormancy period (operating time/total time) of the component. Equation 4-6 shows the updated version of Equation 4-2 for a Weibull distribution with the environmental and dormancy factors added.

$$\frac{dP_{Active}}{dt} = -K_1 K_2 K_3 \times \beta \frac{(td)^{\beta-1}}{\alpha^{\beta}} P_{Active}(t) \qquad [4\text{-}6]$$

where K_1, K_2 and K_3 are K-factors related to general environment of operation, stress level of the component, and the general effect of temperature respectively (USACE, 2001) and d is the duty cycle of the component.

The software application uses a 4th order Runge-Kutta (RK4) method to numerically solve the ordinary differential equation shown in Equation 4-6 and displays the results as both unavailability diagrams and tables.

4.3.2.2 STRUCTURAL COMPONENTS

Modeling the availability of structural components is more complicated; they usually have longer life expectancies and require specific monitoring, testing and rehabilitation procedures. Similar to mechanical components, structural components also experience various degrees of deterioration during their life cycle and can be modeled using a semi-Markov approach. The semi-Markov method used to model the structural components in this software application has been applied in a similar context in bridge monitoring and rehabilitation analysis (Sobanjo, 2011). For the structural components of a spillway gate system, six states of degradation are defined as shown in Table 4-1.

Table 4-1: Condition states and descriptions of a structural component of spillway gate systems

Condition State	Definition
1	Excellent: No member deformation, no cracks, no concrete spalling or erosion, no misalignment
2	Good: Sum of all deterioration and contamination<20%
3	Satisfactory: Sum of all deterioration and contamination between 20-40
4	Fair: Sum of all deterioration and contamination between 40-60%
5	Poor: Sum of all deterioration and contamination>60%, capacity still adequate, missing components
6	Failed: Unable to correctly position or operate the lifting device or the lifting structure, extensive deterioration, loss of concrete section

During inspection and testing, the inspector determines the state of a given structural component. This data can be collected and further used in parametric analysis to determine the Weibull parameters associated with a given component. Given the Weibull parameters related to state transitions, the semi-Markov analysis can determine the probability of the component being in each state at a given time during its service life. Figure 4-4 shows the semi-Markov model with the states and transition rates between states of a structural component.

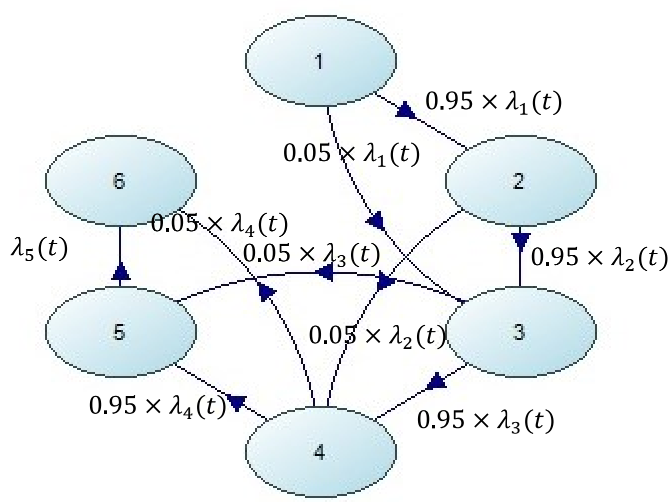


Figure 4-4: Semi-Markov model of a structural component in the dormant phase

As illustrated in Figure 4-4, a new structural component begins in state one and gradually moves to increasing states of deterioration associated with aging, environmental exposure conditions and wear. Under normal operating conditions, there are usually one-step transitions due to deterioration, i.e. the component can change condition states one at a time; however, there have been instances in which a component can experience a two state drop due to an external event. Therefore the software application assumes that 5% of the state transitions to worse states are two-step drops and 95% occur in single steps. Similar to mechanical components, each transition to a worse state is identified by a Weibull hazard rate function denoted as $\lambda_1(t)$ to $\lambda_5(t)$. Equations 4-7 to 4-12 are solved using the RK4 method to determine the probability of the component being in each state at a given time during the dormant phase.

$$\frac{dP_1(t)}{dt} = -K_1K_2K_3 \times \beta_1 \frac{(td)^{\beta_1-1}}{{\alpha_1}^{\beta_1}} P_1(t) \tag{4-7}$$

$$\frac{dP_2(t)}{dt} = K_1K_2K_3 \left[-\beta_2 \frac{(td)^{\beta_2-1}}{{\alpha_2}^{\beta_2}} P_2(t) + 0.95 \times \beta_1 \frac{(td)^{\beta_1-1}}{{\alpha_1}^{\beta_1}} P_1(t)\right] \tag{4-8}$$

$$\frac{dP_3(t)}{dt} = K_1K_2K_3 \left[-\beta_3 \frac{(td)^{\beta_3-1}}{{\alpha_3}^{\beta_3}} P_3(t) + 0.95 \times \beta_2 \frac{(td)^{\beta_2-1}}{{\alpha_2}^{\beta_2}} P_2(t) + 0.05 \times \beta_1 \frac{(td)^{\beta_1-1}}{{\alpha_1}^{\beta_1}} P_1(t)\right] \tag{4-9}$$

$$\frac{dP_4(t)}{dt} = K_1K_2K_3 \left[-\beta_4 \frac{(td)^{\beta_4-1}}{{\alpha_4}^{\beta_4}} P_4(t) + 0.95 \times \beta_3 \frac{(td)^{\beta_3-1}}{{\alpha_3}^{\beta_3}} P_3(t) + 0.05 \times \beta_2 \frac{(td)^{\beta_2-1}}{{\alpha_2}^{\beta_2}} P_2(t)\right] \tag{4-10}$$

$$\frac{dP_5(t)}{dt} = K_1K_2K_3 \left[-\beta_5 \frac{(td)^{\beta_5-1}}{{\alpha_5}^{\beta_5}} P_5(t) + 0.95 \times \beta_4 \frac{(td)^{\beta_4-1}}{{\alpha_4}^{\beta_4}} P_4(t) + 0.05 \times \beta_3 \frac{(td)^{\beta_3-1}}{{\alpha_3}^{\beta_3}} P_3(t)\right] \tag{4-11}$$

$$P_{Failed}(t) = P_6(t) = 1 - [P_1(t) + P_2(t) + P_3(t) + P_4(t) + P_5(t)] \tag{4-12}$$

In the inspection/testing phase, the user has the option to rehabilitate the component from a given state to any improved state. For example, to rehabilitate a failed component to an "as good as old" condition (repair without replacement), the user has to create a transition from state 6 to state 5 and for an "as good as new" condition (replacement with a new component) from state 6 to state 1 as shown by the continuous and dashed transition lines in Figure 4-5.

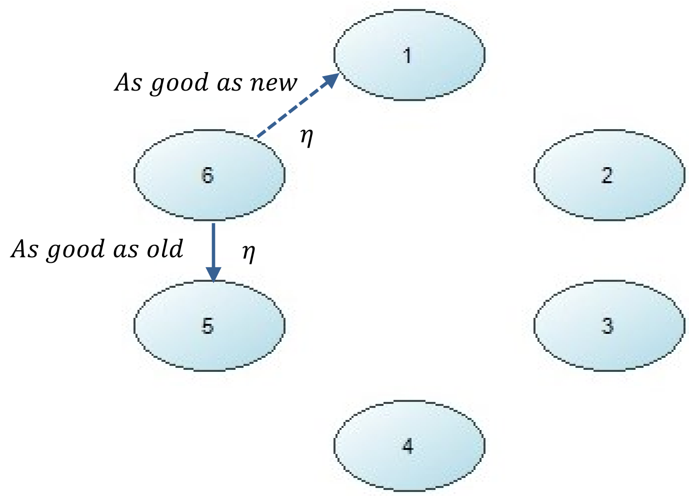


Figure 4-5: Semi-Markov model of a structural component in the inspection/testing phase, demonstrating "as good as old" and "as good as new" rehabilitation scenarios

Figure 4-6 shows the *New Component* dialog box for structural components. The user enters the Weibull parameters for each of the 5 states and then selects a repair strategy as mentioned above.

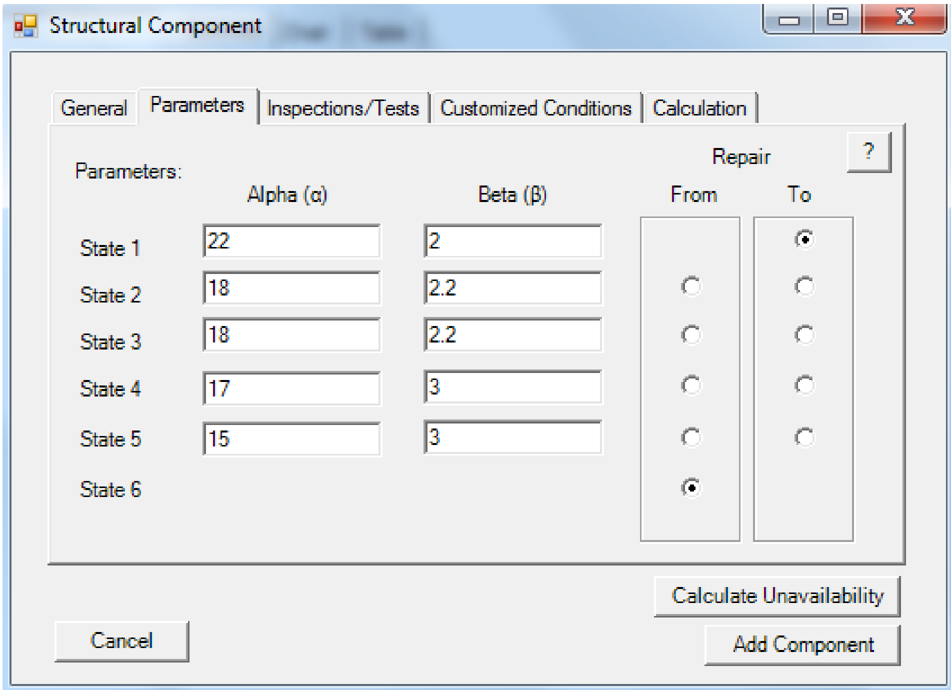


Figure 4-6: New component dialog box for structural components, parameters tab

Once the Weibull distribution parameters and the test efficiencies have been added, the software application determines the unavailability of the structural component (the probability of being in state 6) and the results are displayed in the same manner as electrical/mechanical components. The user also has the option to view the probability of the component being in the other states throughout its service life.

4.3.4 INSPECTION AND TESTING

Periodic inspections and testing are crucial to maintain the safe operation of spillway systems. Preventive maintenance operations usually include visual examination of the component, cleaning and lubrication where necessary and are conducted to facilitate smooth operation of the components. These steps should be taken according to the procedure recommended by the manufacturer at the specific frequency.

Although some components such as emergency power generators can be and are tested separately, the optimum scenario is to perform regular full gate lift tests to ensure that all components function together under full load and realistic conditions. However, due to pool loss, downstream consequences and risk of gate malfunction, it is not always feasible to conduct full gate lift tests. In practice, other less costly tests are favored to avoid fully lifting the gate. These tests include: partial gate lift tests where the gate is lifted only to a small percentage of its full travel and the stoplog test in which stoplogs are placed in the gate opening to retain water and the gate is fully lifted without losing water.

4.3.4.1 INSPECTION AND TESTING EFFICIENCY

Although the tests mentioned above are successful in validating certain aspects of the functionality of the system, it is important to note that they are not always 100% efficient. A partial gate lift test tests all components under full hydro-static load; however, since the gate only opens to a certain percentage of the full travel, it cannot fully detect potential structural issues such as misalignment of the gate structure or jamming of rotating parts. The stoplog test assesses structural issues associated with misalignment but is not efficient in detecting defects related to excess loading since components are not tested under full load. Therefore it is important to consider the efficiency of a test for each component when evaluating component/system unavailability.

As discussed, the efficiency of a test to detect failure may vary for different types of components. For example, a full gate lift test has an efficiency of 100% for all components since it fully tests the entire spillway gate system under realistic scenarios; therefore, the unavailability of all components returns to zero after each full gate lift test. A standard partial gate lift test (~10% of full opening) has high efficiency of failure detection for components related to the equipment subsystem since they are being tested under full load which includes the breakaway load. The breakaway load is the force required for the gate to break free of static friction and begin its upward movement (FEMA, 2010). This force is applied during a short time lapse where the lifting components take additional loading. However, the same test has a low efficiency of detection for the components of the structural subsystem since it cannot detect problems related to configuration and alignment of the structural elements.

In the stoplog test the hydro-static load is completely removed from the gate and the gate is fully lifted. Therefore, it has a low efficiency of detection for the equipment subsystem as realistic loading conditions are not being applied and failure due to overloading may not be detected. However, it has a high efficiency for the structural elements as the gate opens fully and misalignment and configuration issues can be identified.

4.3.4.2 INSPECTION AND TESTING FREQUENCY

Inspections and tests are meant to detect latent failures in order to restore the reliability of components to an acceptable level. Therefore, the dormancy period corresponds to the frequency of tests and/or inspections. In practice, the frequency of tests and inspections varies greatly as a function of the type of equipment and the anticipated failure rate. For example, monthly tests may be appropriate for an emergency generator, while verifying the verticality of embedded parts may only be required after several years to obtain a similar level of reliability.

It is important to note that a high frequency of inspections/tests increases operational costs which must be balanced with benefits in terms of increased availability. Depending on the criticality of the spillway gate system in terms of safety, which can be related to dam classification, redundancy (primarily the number of gates), and reaction time, dam owners can establish a maximum unavailability limit beyond which public safety may be unduly compromised.

In the software application the user first enters all inspections/tests performed on the spillway gate system along with their frequency using the "*Add Test*" option on the top menu. These inspections/tests will be added automatically to a database. The user can later extract any of these inspections/tests from the database when creating components in the fault tree model. Figure 4-7 shows the "Inspection/Test" tab of the "New Component" dialog box for electrical/mechanical components. As demonstrated, the user selects the inspections/tests relevant to the component and enters the efficiency value of the test on that component. This will ensure that the frequency and efficiency of inspections/tests are considered independently for each component of the fault tree model.

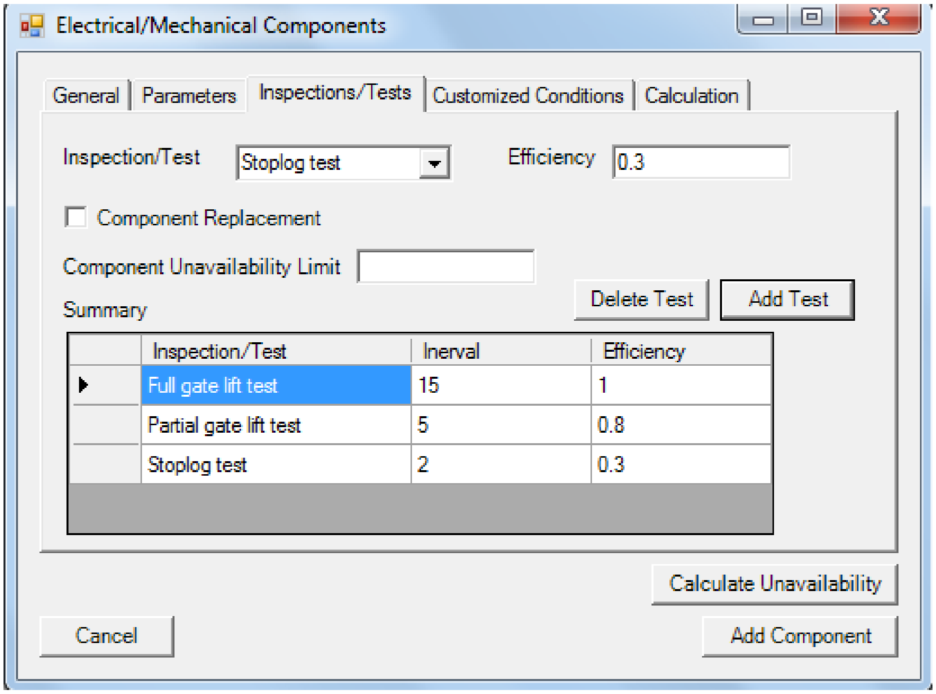


Figure 4-7: New component dialog box for structural components, Inspections/Tests tab

4.4 CASE STUDY: UNAVAILABILITY OF A VERTICAL LIFT GATE SYSTEM USING THE SOFTWARE APPLICATION

In this section, a vertical lift gate is modeled using the fault tree function of the software application and the unavailability of the system is presented as a function of time throughout its service life. Results are displayed by using point unavailability graphs, average unavailability value and histograms.

The vertical lift gate system in this study is equipped with a drum and cable lifting mechanism. It is assumed that this vertical lift gate has an independent lifting mechanism and one emergency power generator. Also, it is assumed that other than the emergency generator and lubricants, which are inspected and tested 5 times per year, three major tests are performed to ensure the availability of the system: partial gate lift test (10% lift), full opening with stoplogs, and full gate lift under full hydrostatic load. These tests are assumed to be conducted routinely and at regular intervals. Maintenance and inspection procedures are performed in accordance with specifications from component manufacturers.

Initially, every test is defined in the software application along with its corresponding frequency. Next, the fault tree is created starting with the top event of *Failure of the vertical gate to open/close* and ending by the basic events of failure at the component level. The top event is divided into two main subsystems: the equipment (electrical and mechanical components) and the structural (civil components). For this study, it is assumed that electrical components have constant failure rates and are modeled using the exponential distribution, mechanical and structural components experience aging and deterioration and are therefore modeled with time-dependent hazard rate functions. As discussed in sections 4.3.2.1 and 4.3.2.2, mechanical components are modeled using the two-state semi-Markov model and structural components are modeled using the six-state semi-Markov model. The Weibull hazard rate function is used as the transfer rate to a worse state for both mechanical and structural components. Parameters of the Weibull hazard rate functions of these components are determined from sources such as the USACE (2001). A list of failure rates associated with spillway gate components may be found in Appendix C. A duty cycle factor (the ratio of operating time over total time) is considered for each component as well as K-factors to account for the environmental exposure conditions. Next, in the inspection/test tab of each component, the inspections/tests which affect the given component are identified and selected from the database and the efficiency of each inspection/test to detect failure of the component is added.

After the fault tree has been completed with component details, and the service life of the spillway gate system is specified, the software application calculates the unavailability of each component as a function of time using the Markov/semi-Markov modules and then transfers the values to the basic events of the fault tree from which the overall unavailability of the system is calculated. Figure 4-8(a) and (b), shows the equipment breakdown and the structural breakdown branches of the vertical lift gate system fault tree built in the project tree control of the software application.

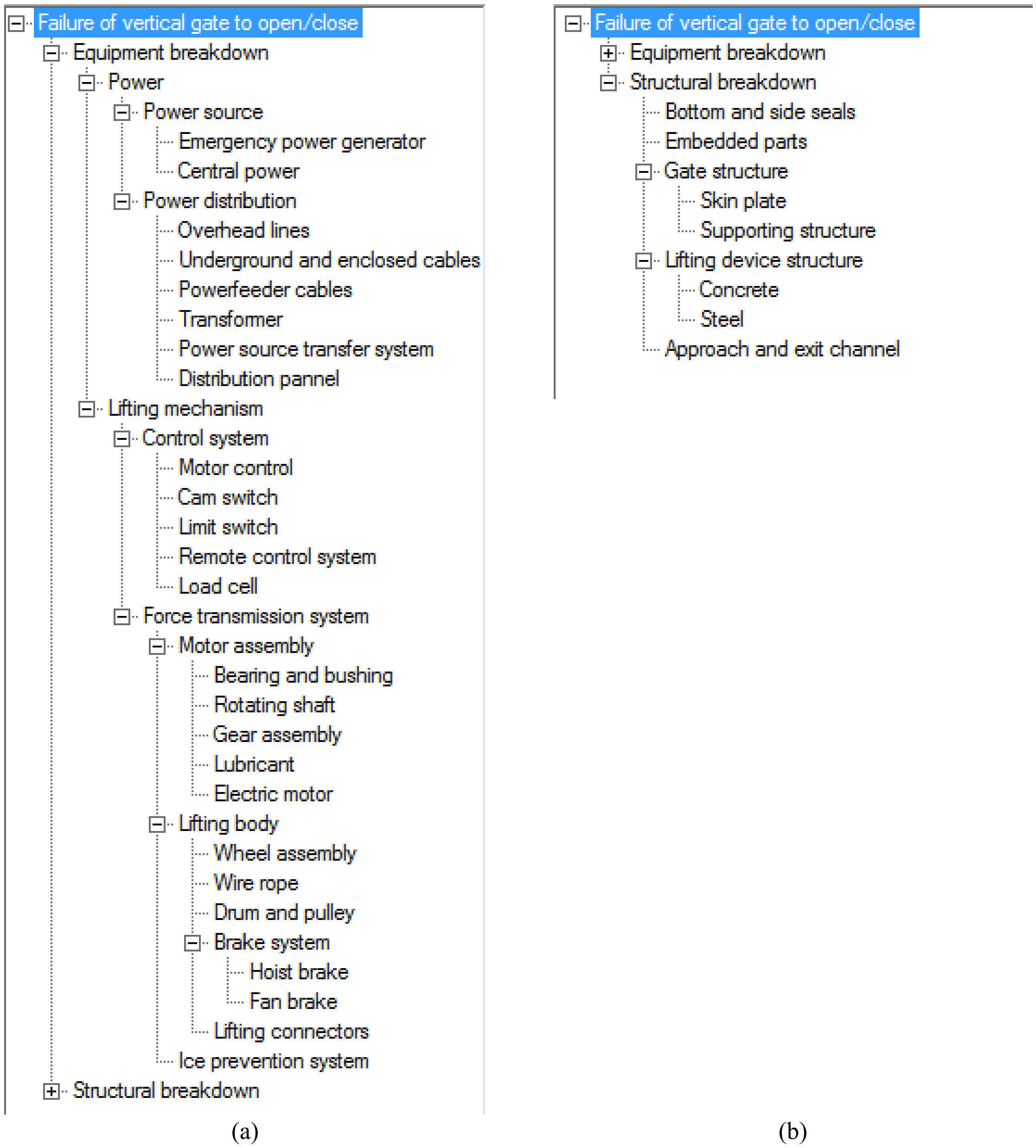


Figure 4-8: Fault tree model of the vertical lift gate system, (a) details of the equipment breakdown branch, (b) details of the structural breakdown branch

As shown in this figure, each of the two main branches contains a complex combination of electrical, mechanical and structural components. Figure 4-9 to Figure 4-12 show the unavailability curves of different types of components developed by the software application. Figure 4-9 shows the unavailability diagram of an overhead electric cable. This component falls into the electrical subsystem category and follows the exponential distribution (memoryless); therefore, no degradation can be noted on the diagram (the unavailability value does not increase with time). The three types of tests (full lift, partial lift and stoplog) all have an efficiency of 100% on this component; hence the unavailability value drops to zero after each test is performed.

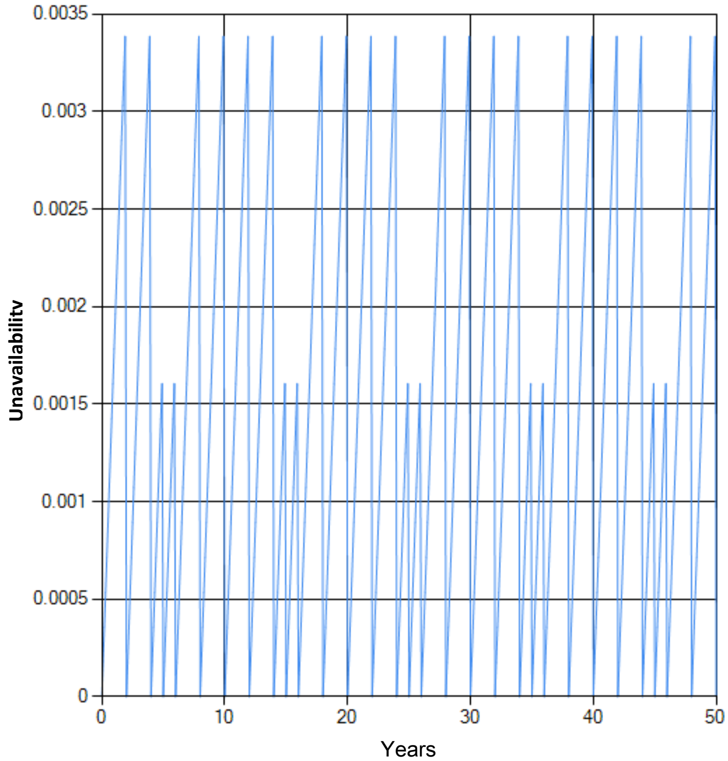


Figure 4-9: Unavailability diagram of the overhead cables

Figure 4-10 shows the unavailability curve of a lubricant (grease) which is in the mechanical subsystem. This component can experience degradation with time due to contamination and therefore follows the Weibull distribution (unavailability increases with time). The lubricant is inspected fully five times per year and the efficiency of the inspection is 100%, thus the unavailability drops to zero after each inspection. Figure 4-11 shows the gear assembly which is part of the mechanical subsystem. The gear assembly can be affected by deterioration with age, such as wear, corrosion and cracks. This component is modeled using the Weibull distribution and is tested every 2, 5 and 15 years with the partial lift, stoplog and full lift tests respectively. The efficiencies of these tests to detect failure of the gear assembly are not all the same. The partial lift test has an efficiency of 80% as it is performed under full hydro-static load. The stoplog test has an efficiency of 20% since it is performed under no load and the full lift test has an efficiency of 100%. Therefore, the unavailability of the gear assembly drops to zero every 15 years with the full lift tests but drops partially in between depending on whether a partial lift or stoplog test is performed.

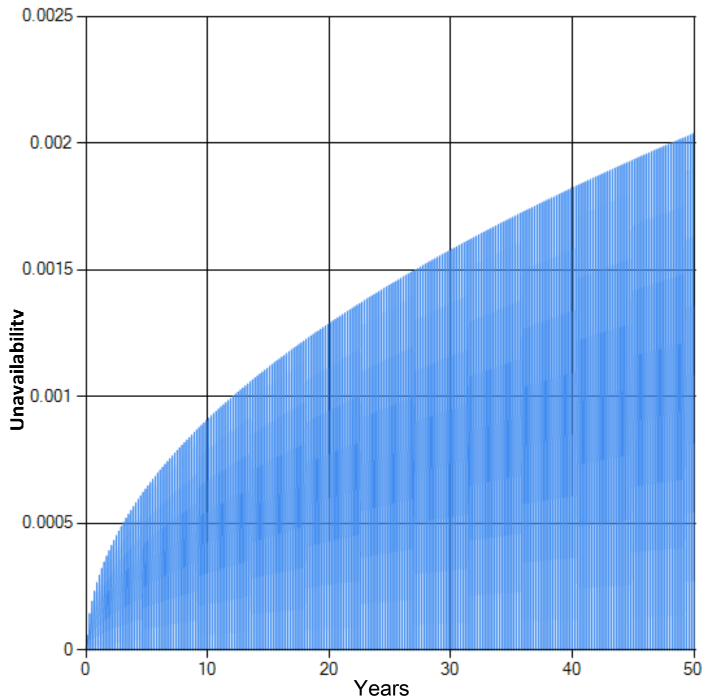


Figure 4-10: Unavailability diagram of lubricant (grease)

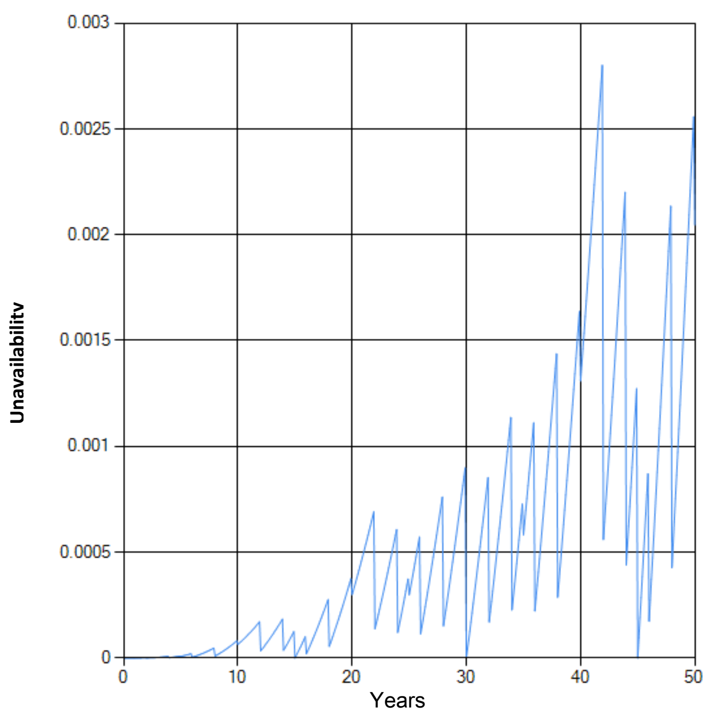


Figure 4-11: Unavailability diagram of the gear assembly

Finally, Figure 4-12 shows the unavailability diagram of the embedded parts which are in the structural components subsystem. This component also follows the Weibull distribution and experiences deterioration due to corrosion, missing elements, etc. Structural components have lower failure rates compared to electrical, mechanical components therefore, the unavailability curve of the embedded parts does not increase as sharply as the previous components; however, it may be seen that the unavailability increases more rapidly as the component ages and experiences the wear-out phase. Similar to the gear assembly, this component is modeled using the Weibull distribution and is tested every 2, 5 and 15 years with the partial lift, stoplog and full lift tests. These tests however, do not have the same efficiency of failure detection as with the gear assembly. The partial lift test has an efficiency of only 10% since the gate is lifted only up to 10% of its full travel path. Conversely, the stoplog test has an efficiency of 70% since the gate is lifted fully but under no load and the full lift test has an efficiency of 100%.

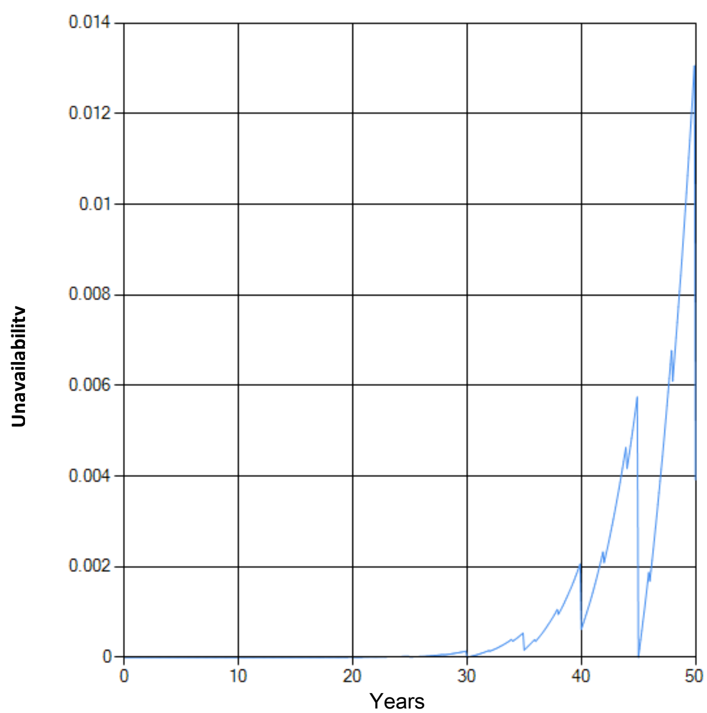


Figure 4-12: Unavailability diagram of the embedded parts

Figure 4-13 shows the unavailability diagram of the vertical lift gate system along with its two main branches equipment breakdown and structural breakdown.

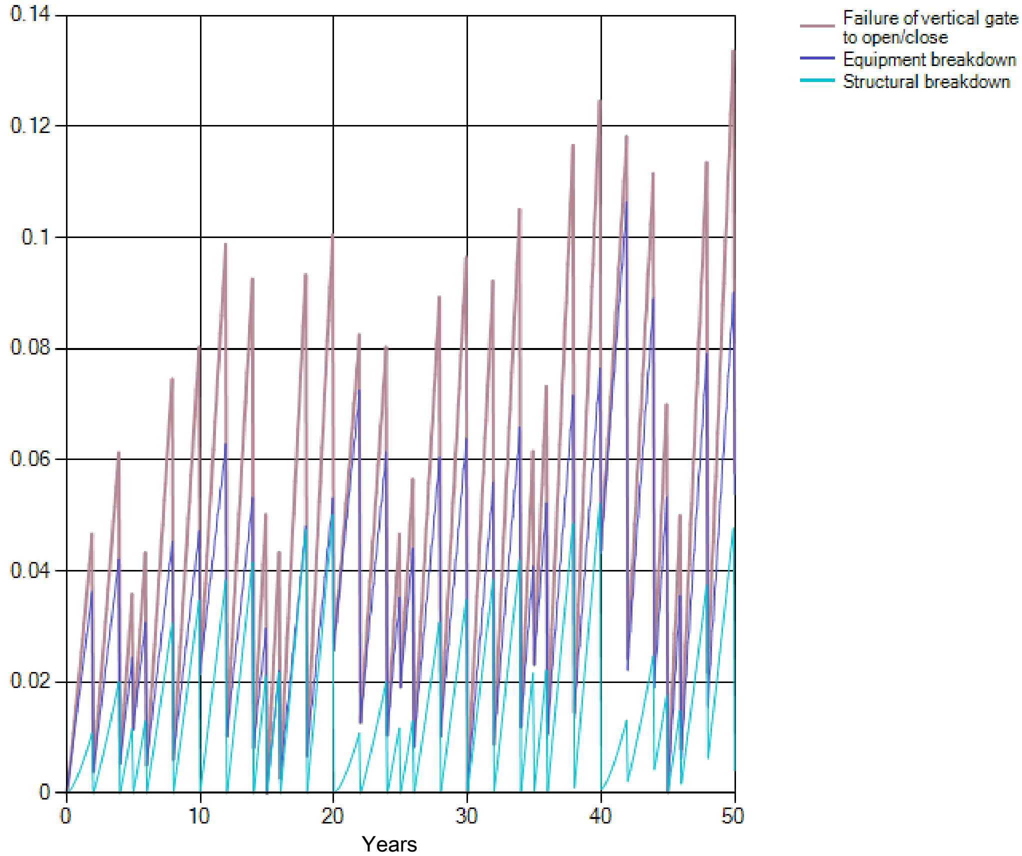


Figure 4-13: Unavailability of the vertical lift gate and the two main branches of the fault tree

Figure 4-13 illustrates that in this case study; the unavailability of the vertical spillway gate system is mostly governed by the equipment (mechanical and electrical) subsystem which has the highest unavailability. These results are consistent since in reality structural components are designed and expected to maintain functionality longer than electrical and mechanical component and therefore deteriorate at a slower rate relative to electrical and mechanical components.

It is important to note that in this study, most failed component are restored to conditions before failure (as good as old) after the end of a dormant interval and there is no component replacement until the components reach a predefined unavailability limit after which they are completely replaced (as good as new). Also in this study, the 10% gate lift test (performed every two years) has an efficiency of 80-100% for the electrical and mechanical subsystem. This same test however, has an efficiency of less than 40% on the structural subsystem. The stoplog test (performed every 5 years) also has different efficiencies for each subsystem.

As previously mentioned, the software application also has a histogram feature from which the user can view the unavailability histogram of any event/component of the fault tree. Figure 4-14 shows the unavailability histogram of the vertical lift gate system. It may be seen that for the 50 year life cycle and the existing inspection/test strategy of this gate the most likely unavailability value is approximately 4%.

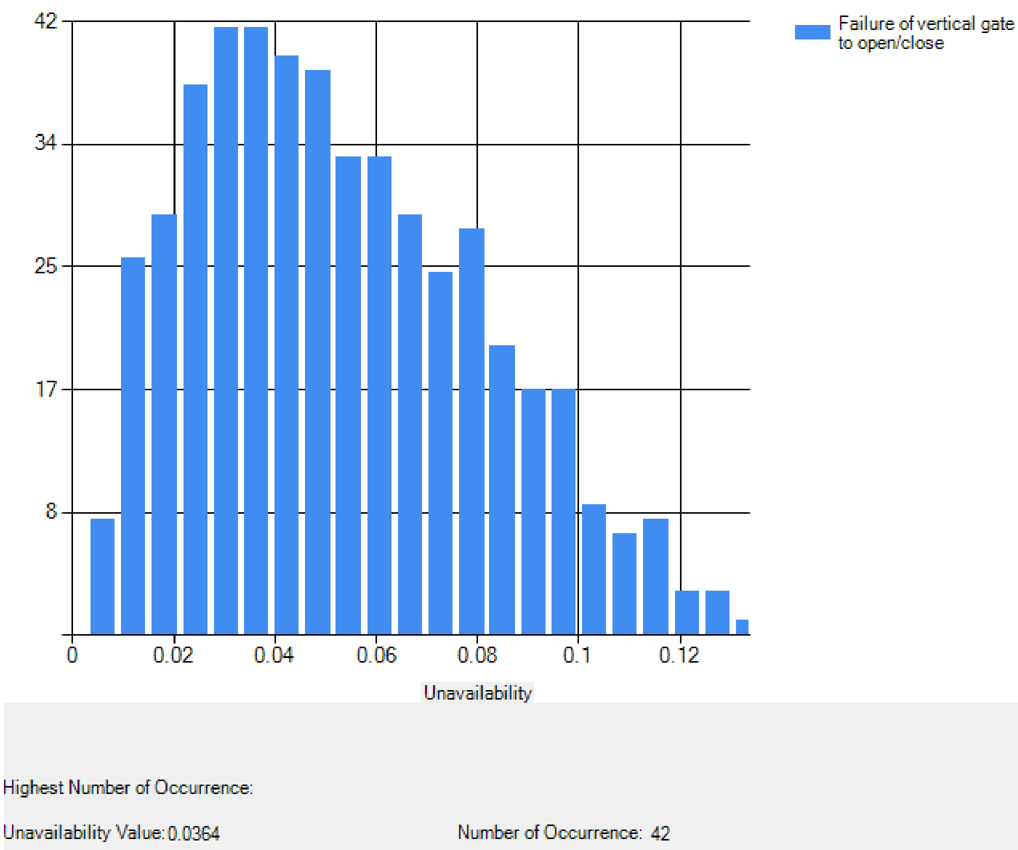


Figure 4-14: Unavailability histogram of the vertical lift gate system

This option of the software application can assist in providing the user with an estimation of the mean unavailability of the system as a quantitative measure to compare with unavailability limits set by dam owners and dam classifications when designing preventive maintenance, inspection and testing strategies for a given spillway gate system.

4.5 CONCLUSION

The purpose of this article was to introduce a state-of-the-art software application developed to determine the unavailability of spillway gate systems. Spillway gates are usually dormant and are located in remote areas and subjected to severe environmental conditions. Both point and average unavailability of a spillways gate system are essential tools for engineers when developing maintenance and testing strategies to ensure the safe operation of the system. Also, consideration of the effects of dormancy, environmental conditions, type and frequency of inspections/tests are critical to accurately determined the unavailability of the spillway gate system and maintain this value within acceptable limits.

This software application uses built-in reliability techniques such as fault tree, Markov and semi-Markov analysis to model the dormant behavior of the spillway and incorporates the environmental condition by assigning updating factors within the model.

As both the efficiency and the frequency of inspection/testing can significantly affect the reliability of the gates, this software application integrates the inspection and testing strategy of the spillway system both in terms of type (efficiency) and frequency. It is important to recognize that the efficiency of a given test to detect failure may be different from one component to another and this can be indicated by varying the efficiency of tests for different types of components.

With these options incorporated in the software application, the user is able to determine the unavailability of system and all its components at any point in time and hence develop the optimum inspection and testing plan both in terms of system reliability and cost. This should result in a rationalization of financial resources and personnel by eliminating practices that contribute little to overall reliability while ensuring the safe operation of the spillway gate system.

CHAPTER 5: MANUSCRIPT 3

AN OBJECTIVE PROCEDURE FOR THE OPTIMIZATION OF INSPECTION AND TESTING STRATEGIES FOR SPILLWAYS

Maryam Kalantarnia, Luc Chouinard, Stuart Foltz

ABSTRACT

The function of a spillway gate system is to control the flow of water through an opening and it is generally used for various purposes such as flow regulation, flood control, emergency water release during load rejection, dewatering for maintenance operations, or to remediate or respond to structural deficiencies. Spillway gate systems vary in type, size and number of gates based on dam classification, purpose and downstream failure consequences. A growing problem for dam owners is the aging of such structures. Older spillways require more rigorous maintenance, inspection/testing and repair/replacement of parts in order to ensure their long-term safe operation and if neglected may pose serious risks to persons and property. Executing these measures may be very costly to dam owners and if not conducted appropriately may not have the desired effect on the reliability of the system. Therefore, it is important to evaluate the effect of such preventive/corrective measures on the reliability of spillways gate systems to develop the optimum strategies and guidelines.

The first objective of this paper is to demonstrate the effect of inspection, testing, repair and replacement options on different types of components of the spillway gate system in maintaining the unavailability below the limit defined by the dam owners or regulators based on dam classifications and standards. The second objective is to evaluate the availability of the entire spillway gate system under flood and load rejection scenarios in order to determine the ability of the system as a whole to operate safely under emergency conditions. These two objectives are then used with cost optimization to develop recommendations on the type and frequency of inspections and tests for different types of spillway gate systems. A software application was developed to achieve the above objectives by modeling the spillway gate components and system, determining

component/system unavailability based on type and frequency of inspections/tests and obtaining the optimum inspection/testing strategy.

KEYWORDS: Spillway gate system, unavailability, inspection and testing, optimization, flood, load rejection, software application

5.1 INTRODUCTION

The aging state of current dams indicates that spillways are becoming more prone to failure. As the consequences of dam failure can be catastrophic and could involve loss of life, it is critical to develop procedures to evaluate the reliability and risk associated with spillways and to develop mitigation procedures that may also include warning systems in the event of a possible flood inundation due to a dam breach. In order to ensure the safety of people and properties downstream a dam, the discharge of water from a spillway gate system must be safely controlled at all times. The responsibility for the safe operation of the spillway falls on to the dam owners. Therefore, it is important that owners, particularly owners of older dams, recognize the importance of an effective maintenance, inspection and testing strategy which can proactively manage the risk associated with the aging of such structures. ASCE, FEMA, the National Dam Safety Review Board and the US Army Corps of Engineers (USACE) have jointly developed guidelines on the safe operation, maintenance, inspection and testing of water control gates (FEMA 2010). The United States Society on Dams (USSD) also provides a thorough overview of spillway gate systems and reviews industry guidelines for the evaluation of maintenance, inspection and testing procedures of spillway gate components (USSD, 2002). ANCOLD guidelines provide detailed risk assessment approaches to ensure a high level of reliability for dam structures (ANCOLD, 2003).

The types and frequency of inspections/tests as well as the unavailability limit of spillway gate systems may vary based on dam classifications. In Quebec, dam classifications are defined in the Dam Safety Act which prescribes a series of measures governing the operation of dams. In particular, it requires that dam owners conduct regular maintenance, inspections and tests on the dams to ensure their good condition (2002). Dams are classified based on the degree of risk posed on persons or property. Dams are classified from A (large, high failure consequence) to E (very low consequence) using an index called the "P value" measured by multiplying a dam vulnerability index (V) with a potential consequences of failure index (C) (2013). The vulnerability (V) of a dam is a function of invariant physical parameters such as dam height, dam type, impounding capacity and dam foundation type and time-variant parameters such as dam age, seismic zone, dam condition (physical state and structural condition) and the reliability of discharge facilities. Potential consequences of failure are determined based on downstream population density and extent of infrastructure. The frequency of inspections and safety reviews are a function of dam classification.

Several methodologies have been proposed to ensure the safety of spillway gates in terms of operation and equipment, and to best allocate rehabilitation resources to address the most critical deficiencies. Risk assessment and reliability analysis have been the main tools for these purposes. Briand et al. (2009) developed a risk ranking approach which provides a global ranking index based on capacity, vulnerability and functionality of each spillway gate system. Putcha and Patev (2000) summarize current reliability and risk assessment practices for spillway gate systems such as Failure Mode and Effect Analysis (FMEA) and Fault Tree/Event Tree Analysis (FTA/ETA). Although a variety of different reliability methods exist, most do not accurately reflect the reliability of spillway gate systems. Spillway gates are complex systems comprised of electrical, mechanical and structural components exposed to site specific environmental conditions. The dormant nature of spillway gates also adds to the complexity of the system since failures go undetected until a demand. Therefore, it is important to consider these factors in the reliability analyses. Estes and Foltz (2006) propose an approach to estimate the reliability of a deteriorating system using condition assessments derived from inspections and tests which was extended by Chouinard, et al. (2008) and Kalantarnia, et al. (2011) to include dormancy effects associated with testing and inspections.

This paper has two main objectives:

- To demonstrate the effects of inspection, testing, repair and replacement options on different types of components of the spillway gate system.
- To evaluate the availability of the entire spillway gate system under flood and load rejection scenarios in order to determine the ability of the system as a whole to operate safely under emergency conditions.

A software application developed by the authors is used to achieve the above objectives by modeling the spillway gate components and system and taking into account environmental conditions and dormancy. The software determines the component/system unavailability based on type and frequency of inspections/tests and identifies the optimum inspection/testing strategy using a benefit/cost analysis. The software application is described in Chapter 4. Using this software, recommendations are formulated on the type and frequency of tests and inspections for common types of spillway gate systems.

First, examples of existing practices on inspection/testing strategies are reviewed, followed by the objectives, architecture, features and methods of analysis employed in the software application. The procedures are used to determine the range of achievable availability of the electrical and mechanical components of a typical spillway gate system as a function of frequency and type of inspections/tests. These results are combined to determine the availability of the entire spillway gate system during flood and load rejection scenarios. Cost optimization is then used to determine the optimum inspection/testing strategy in terms of availability and cost, considering cost of inspections/tests and consequences of failure. Finally, a summary the results and recommendations are presented.

5.2 REVIEW OF CURRENT INSPECTION/TESTING PRACTICES

According to the United States Society on Dams, there are two critical scenarios of spillway gate failure: the first scenario is an operation failure due to gate, hoist, and/or control problems resulting in loss of spillway flow regulation. This scenario can cause the failure of the gates to open or close. The inability to close a gate may result in loss of valuable water supply or flooding of the downstream channel. The inability to open a gate can result in overflow and ultimately to breaching of the dam. Failure to operate a spillway gate may be due to issues such as increased gate and hoist friction forces, inoperable hoist or control components, and loss of prime and auxiliary power. The second scenario is the physical failure/collapse of a gate resulting in an uncontrolled release of water into downstream channels, resulting in potential property damage and loss of life, and loss of valuable water (USSD, 2002). The purpose of periodic gate inspection, maintenance, and test-operation is to ensure that the above scenarios and related causes do not occur.

Maintenance can range from visual inspection, cleaning and greasing of components to complete overhauls and replacement of parts. Periodic maintenance such as adjustment, alignment, lubrication and replacing of missing elements such as nuts and bolts are essential to the long term operation of gate parts. Such tasks should be done regularly and according to the instructions of the manufacturer. FEMA recommends that a schedule of routine maintenance activities and their result be documented in permanent records for all electrical, mechanical and structural components of the spillway gate system (FEMA 2010).

Other than maintenance of components, visual inspection and functional test-operation of gates are the most practical ways of determining the overall level of reliability of a spillway gate system. The type and frequency of inspections/tests depends on the gate type, function and classification of the spillway gate system. FEMA categorizes gate inspections into informal, intermediate, periodic, close-up and unscheduled inspections. Informal inspection is a non-specific visual inspection for potential deficiencies while intermediate inspection is a walkthrough of all gate components and operating systems. Periodic inspection is a more thorough observation of components performed at regular intervals. For close-up inspections, all components, including the structural and operating systems are visually inspected within a 2ft distance. Finally, the unscheduled inspection is performed when deficiencies or problems have developed in between regular inspections (FEMA 2010).

Flood control and emergency gates which are operating infrequently (dormant) should be tested regularly. Although some components such as emergency power generators can be and are tested separately, the optimum scenario is to perform regular full gate lift tests to ensure that all components function together under full load and realistic conditions. However, due to pool loss, downstream consequences and risk of gate malfunction, it is not always feasible to conduct full gate lift tests. In practice, other less costly tests are favored to avoid fully lifting the gate. These tests include: partial gate lift tests where the gate is lifted only to a small percentage of its full travel under design load and the full travel no-load stoplog test in which stoplogs are placed in the gate opening to hold the water and the gate is fully lifted without losing water. FEMA recommends the partial lift and stoplog tests to be conducted at least each 1-2 and 5-10 years respectively (FEMA 2010).

Although these tests are successful in validating certain aspects of the functionality of the system, it is important to note that they are not always 100% efficient for all components. A partial gate lift test, although performed under full load, cannot fully detect potential structural issues such as misalignment of the gate structure or jamming of rotating parts. The stoplog test assesses structural issues associated with misalignment but is not efficient in detecting many defects since components are not tested under full load. Therefore it is important to consider the efficiency of a test for each component when evaluating component/system unavailability.

5.3 METHODOLOGY AND SOFTWARE APPLICATION

Spillway gates are complex systems with customized components subjected to long periods of dormancy under severe environmental conditions. These circumstances make it very difficult to accurately determine the reliability of such systems and require modifications to standard reliability analysis procedures.

The modifications include considerations of component type, dormancy period, environmental conditions and inspection and testing strategies. The procedure is implemented in a software application to facilitate the analysis for complex systems, with various inspection, testing and component replacement options. Results are presented in terms of the availability of the system as a function of time during the projected service life, the optimal inspection and testing strategy is identified as a function of the minimum unavailability limit set by the owner or regulator and a benefit/cost analysis. Reliability analysis methods featured by this software include Markov/semi-Markov analysis, Fault Tree analysis and optimization techniques based on the Random Search method and Genetic algorithms.

5.3.1 FAULT TREE ANALYSIS

The application allows users to create fault tree models by generating events, components and their interactions. For this study, a spillway gate system is modeled with “failure of gate to open/close" as the top event. The top event is then further extended to include three branches representing the failure of the three main subsystems of equipment, structural and operational. The equipment branch comprises events related to the performance of the lifting mechanism and power supply (electrical and mechanical subsystems) while the structural branch comprises events related to the performance of the skin plate and the structural components of the gate (civil subsystem). Investigation of operational failures is not within the scope of this paper and therefore is not discussed further. The basic events of the fault tree, which represent the root causes of the top event, are component failures

Once all the basic events are identified and the failure parameters of the components are defined, the unavailability of the spillway gate system is determined by applying Boolean algebra for each branch of the tree from bottom to top.

5.3.2 MARKOV/SEMI-MARKOV ANALYSIS

Components of most spillway gate systems spend the majority of their service life in a dormant state and are activated randomly (i.e. for high flows or load rejection) or on a regular basis for inspection and testing. Also, most spillways are located in remote areas and are subjected to severe environmental condition which can cause early deterioration of components. Therefore, to determine the availability of spillway gate components the approach needs to account for both dormancy and environmental conditions.

Markov analysis is a reliability modeling approach used for systems which transit from one state to another (Ebeling, 1997). Therefore Markov analysis is appropriate for modeling dormant systems in which a funcational component can fail whithout detection (latent failure). This type of failure can only be detected if the system is activated. To model the components of a spillway gate system using Markov analysis, each component has two states, active or failed. A Markov model generally assumes constant rates of transition between states, which implies that the system has no memory of previous states and that deterioration of components is not considered. This however is an oversimplification for many components of a gate. Mechanical and structural components are subjected to various degrees of deterioration as a function of time and environmental exposure conditions, which can be modeled more appropriately with the Weibull distribution in a semi-Markov approach. This approach has been used for modeling the deterioration of structural components in bridges where the Weibull hazard rate function defines the transition rates between the various levels of deterioration of a component (Ng, et al., 1998). The cumulative distribution function for the time to failure for a Weibull distribution is:

$$F(t) = 1 - \exp[\left(\frac{t}{\alpha}\right)^{\beta}] \qquad [5\text{-}1]$$

where α is the scale parameter and β is the shape parameter of the distribution. The exponential distribution is a special case of the Weibull when β is equal to 1. The Weibull model accounts for degradation of performance as a function of time which is observed for most mechanical and structural components of a gate. Conversely, the exponential distribution is memoryless which implies that there is no deterioration in performance and that failure occurs at a constant rate throughout the lifetime of the components. This type of distribution is often applied to electrical components.

When components are inspected or tested after each dormancy period, the probability of detecting a failure depends on the type of inspection/test performed and in particular if the demands on the component are comparable to those during emergencies. If the component is determined to be operable (active state), the component is kept in service and remains in its current state; however, if a failure is detected, the component is assumed to be repaired and returned to its condition prior to failure (as good as old). This simplifying assumption is used to analyze the effect of testing/inspection on the reliability of a deteriorating system. However, in practice, failed component are replaced by new components. The user also has the option of specifying that components are replaced by new components after a given period of service life or when a specified unavailability limit has been exceeded. The replacement occurs at the next scheduled test/inspection. Also, since in most spillways the dormancy period is much larger than the inspection/testing period, inspection time and repair time are considered negligible with respect to the dormancy period. This assumption is used for demonstration purposes but long repair periods can occur if components are unique in their design or if a latent failure is associated with major structural components and should be accounted for in the model.

The effect of operating conditions on components is modeled by modifying a baseline hazard rate function with K-factors,

$$\mathrm{h}_{\mathrm{modified}} = h_{baseline} \cdot K_1 \cdot K_2 \cdot K_3 \quad [5\text{-}2]$$

where K_1, K_2 and K_3 are K-factors related respectively to environmental exposure, the level of demand on the component, and the effect of operating temperature (USACE, 2001). The effect of dormancy on the failure rate is modeled through a duty cycle factor defined as,

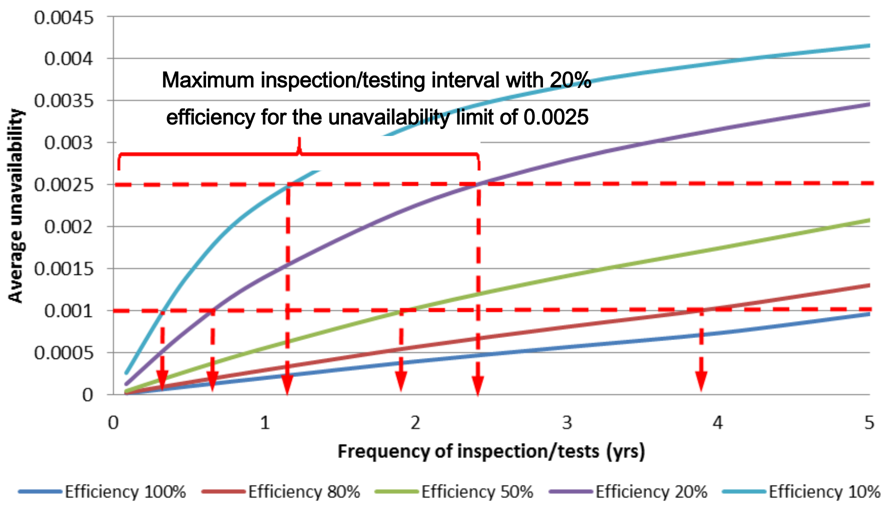
$$\mathrm{DF} = \frac{\text{Operating time}}{\text{Total time}} \quad [5\text{-}3]$$

A RK4 algorithm is used to solve the system of ordinary differential equations resulting from the semi-Markov models.

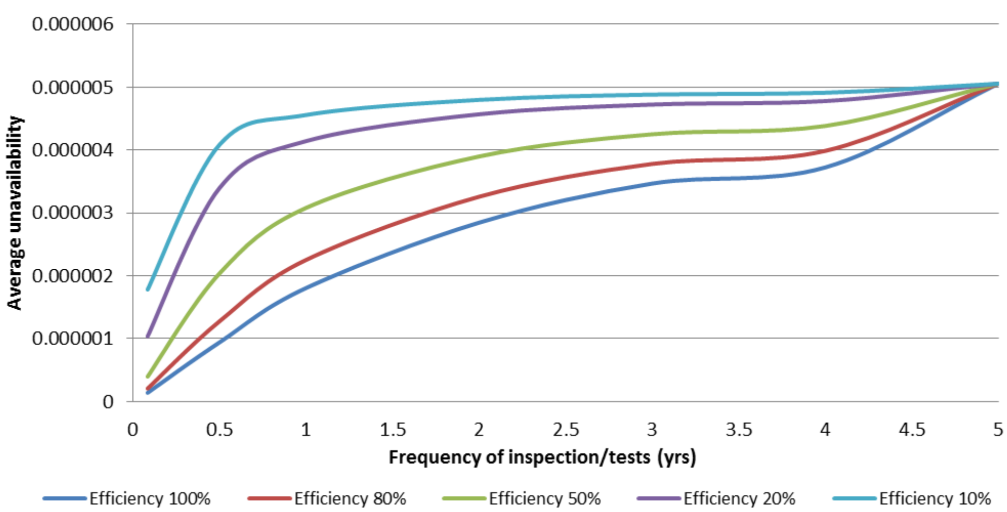
5.4 EFFECT OF TYPE AND FREQUENCY OF INSPECTION/TESTING ON THE AVAILABILITY OF SPILLWAY COMPONENTS

As discussed in section 5.3.2, the efficiency of a given test to detect failure may vary from one component to another. For example, a full gate lift test under full hydro-static load has an efficiency of detection of one for all components since it fully tests the entire spillway gate system at design level demands; therefore, the availability of all components is reset to 100% after each full gate lift test. A standard partial gate lift test (~10%) has a high efficiency of failure detection for components related to the lifting mechanism since the initial breakaway load is greater or equal to the load under full hydraulic conditions. However, this test has a lower efficiency of detection for components of the structural subsystem since it is performed over a small portion of the full gate travel and can miss problems related to the configuration and alignment of structural elements. In the stoplog test, the hydro-static load is completely removed from the gate and the gate is fully lifted. Therefore, it has a low efficiency of detection for the components of the lifting mechanism as realistic loading conditions are not being applied and failure due to overloading may not be detected. However, the test has a high efficiency for some structural elements since misalignment and configuration issues can be identified over the full length of travel of the gate.

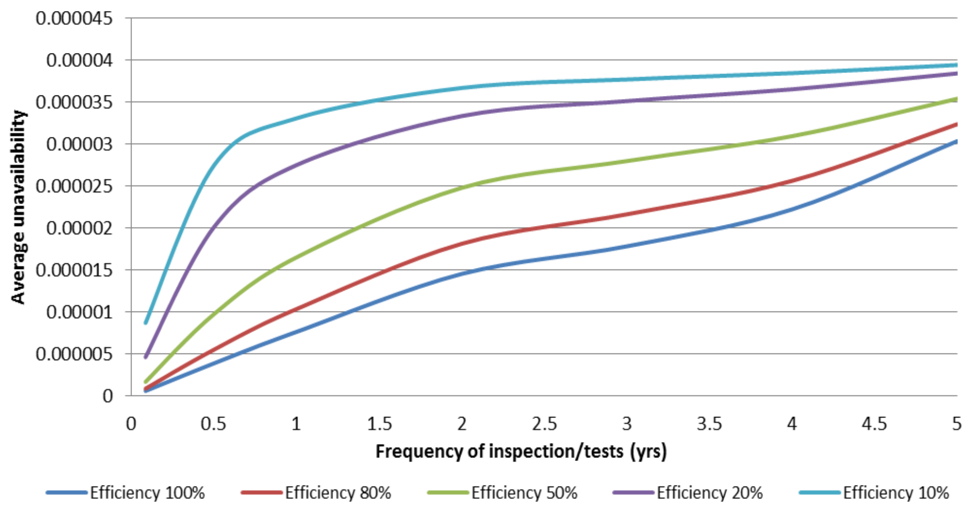
Figure 5-1 shows the average unavailability of a gear assembly (an example of a mechanical component) as a function of inspection/testing frequency for different failure detection efficiencies corresponding to different types of tests. Figure 5-1(a) shows the average unavailability when no replacement is involved, while in Figure 5-1(b) and (c) the component is systematically replaced every 5 and 10 years respectively. The average unavailability is taken over the assumed 50 year service life of the component.



(a)



(b)



(c)

Figure 5-1: Average unavailability of a gear assembly as a function of inspection/testing frequency (a) without replacement, (b) component replacement every 5 years, (c) Component replacement every 10 years

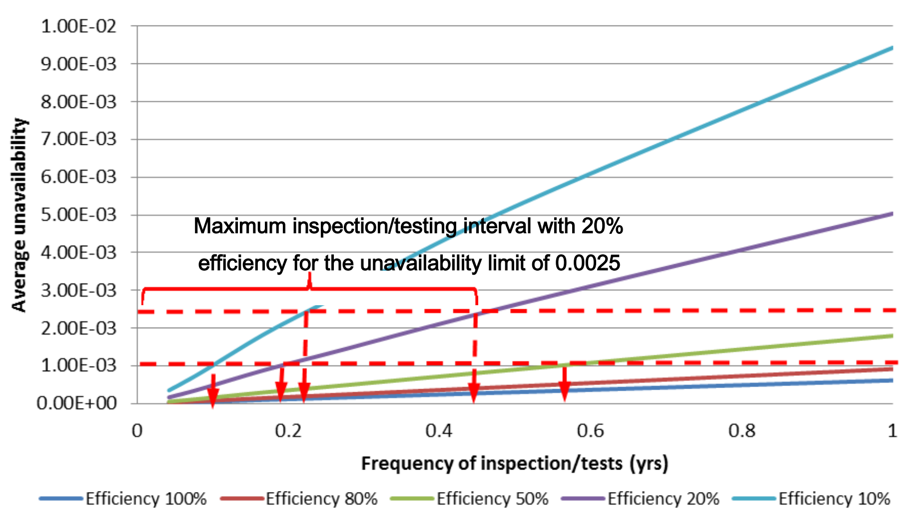
The availability of the gear assembly is determined using the Weibull distribution ($\alpha = 40,\ \beta = 3$) to demonstrate the aging process of the component. A duty cycle factor of 0.1 is also added to account for dormancy of the component as well as K-factors of $K_1 = 2,\ K_2 = 4,\ K_3 = 1.3$ to show the effects of the general environmental conditions, stress level and temperature respectively. For this example, the value of K_1 represents marine or coastal environments, K_2 is associated with a percentage of component nominal rating equivalent to 140%, and K_3 represents component operating temperature of up to -40℃ (USACE, 2001). As illustrated in Figure 5-1(a), when no replacement is involved, the average availability (taken over the 50 years life cycle of the system) increases with an increase in the inspection/testing frequency. Longer inspection/testing intervals mean that components remain dormant for longer periods of time which in turn increases the likelihood of a latent failure due to degradation and environmental conditions. It may also be observed that the average unavailability increases for inspections/tests with lower efficiencies.

As discussed earlier, the maximum acceptable level of unavailability of a spillways system may depend on dam classification and downstream consequences. The time interval for a given inspection/test can be determined from the average unavailability curve of the system and the unavailability limit for a particular class of dam. Figure 5-1 (a) shows how the maximum inspection/testing intervals change with different unavailability limits. With an aggressive unavailability limit of 0.001, a test with 10% efficiency of failure detection needs to be conducted every 3 months; however, the average unavailability for the component undergoing a 100% efficient test remains within limits even when the interval is as large as 5 years. With a higher unavailability limit of 0.0025, tests with efficiencies of more than 50% can be conducted with intervals larger than 5 years and still remain within the acceptable limits, the tests with 10 and 20 % efficiencies need to be applied every 1.2 and 2.4 years respectively to meet the unavailability requirements. This shows that especially with high risk dams with lower unavailability limits, it is important to identify and select inspections/tests with a high efficiency of failure detection for each given component in order to maintain unavailability within limits while reducing the number inspections/tests required.

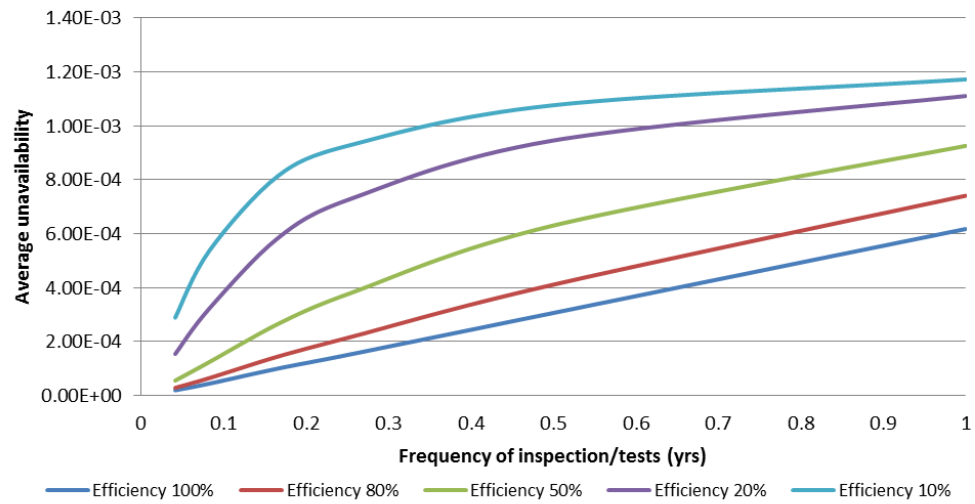
Figure 5-1(b) shows the availability of the same component undergoing the same types of inspections/tests but with a systematic replacement every 5 years. It may be seen that the average unavailability reduces significantly compared to the no-replacement case of Figure 5-1(a) and also with respect to longer periods between replacements such as every 10 years as shown in Figure 5-1(c). As illustrated in Figure 5-1(b), the average unavailability in all cases is similar to inspection/test intervals of 5 years. This is due to the fact that the component is replaced every 5 years regardless of the type of inspection/test conducted. If the inspection/testing intervals exceed the 5 years of replacement than the average unavailability for each test type decreases as the component is restored to “as good as new” conditions every 5 years. Figure 5-1(c) also shows the average unavailability with respect to inspection/testing intervals for different types of inspections/tests and replacement every 10 years. As shown in this figure, the average unavailability is higher with respect to Figure 5-1(b), hence, the average unavailability increases as the period between replacements increases. This is due to the fact that the component is allowed to age more and experience more degradation before being replaced.

Figure 5-2 shows the average unavailability of a motor control system (an example of an electrical component) with respect to the frequency of inspection/test. The exponential distribution is generally used as the failure probability distribution of these components. The exponential distribution is memoryless indicating that failure occurs randomly throughout the service life of the component. In this example the failure rate of the motor control is $\lambda = 0.012$ per year. Duty cycle and K-factors are the same as those for the gear assembly example discussed above. Similar to Figure 5-1, Figure 5-2(a) shows the average unavailability of the motor control without replacement while Figure 5-2(b) and (c) show unavailability with replacement every 2 and 5 years respectively. In Figure 5-2(a) the average unavailability of the motor control increases with the increase in length of inspection/testing intervals which is similar to Figure 5-1(a).

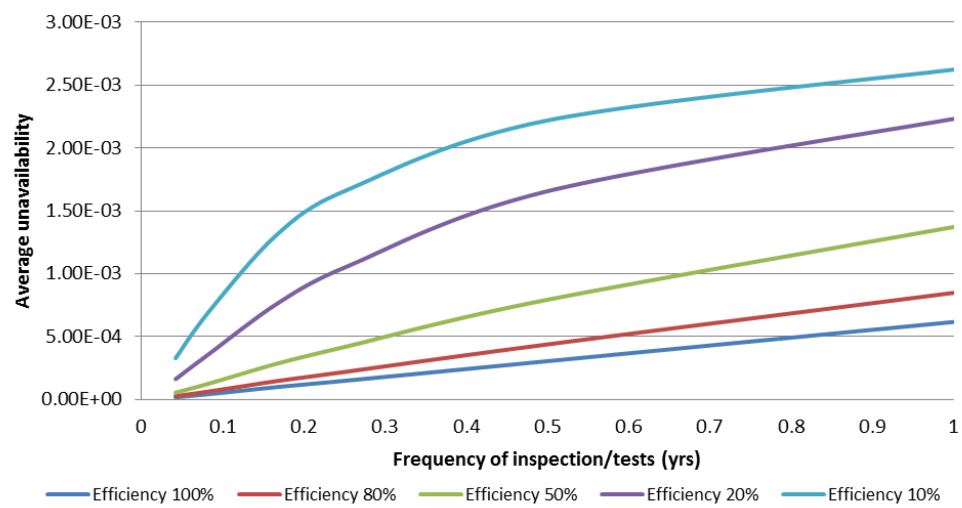
Figure 5-2(a) shows the maximum intervals for different types of tests for the same unavailability limits as Figure 5-1(a). As shown, even with the unavailability limit if 0.001, the two high efficiency tests (100 and 80%) remain within acceptable limits for intervals of less than 1 year. Similar to the previous example, the lower the efficiency of inspections/tests, the smaller the intervals are in between each test. Figure 5-2(b) and (c) show the reduction in the average unavailability of each type of test with a component replacement policy of every 2 and 5 years.



(a)



(b)



(c)

Figure 5-2: Average unavailability of a motor control system as a function of inspection/testing frequency (a) without replacement, (b) component replacement every 2 years, (c) Component replacement every 5 years

This example demonstrates the importance of conducting high efficiency inspections/tests in order to the maintain component availability as high as possible and prevent excess costs associated with avoidable component replacement. Inspections/tests with low efficiency although costly, are not able to detect component deficiencies which may lead to failure under realistic loading conditions, very high efficiency inspection/tests such as the full gate lift test may also be too expensive to conduct regularly, therefore optimization of inspection/testing strategies is required to ensure that both aspects of availability and cost are considered when selecting type and frequency of inspections and tests. The concept of inspection/testing optimization and methodologies is discussed in detail in Chapter 5.6.

5.5 SPILLWAY GATE SYSTEM AVAILABILITY

In this section a spillway gate system with four vertical gates is presented as a case study. Vertical lift gates can have either an independent or a common lifting mechanism. With an independent lifting mechanism, each gate is equipped with its own motor assembly and lifting body; however, with a common lifting mechanism the motor assembly and lifting body is mounted on a gantry crane which moves from one gate to another, lifting the gates one at a time. Depending on the number of gates, a spillway system with common lifting mechanism can have one or more gantry cranes. In the first part of this section the unavailability of a single vertical gate system is determined using the software application discussed earlier. The second and third parts show the unavailability of the spillway system with four gates under load rejection and flood scenarios respectively for both independent and common lifting mechanisms.

5.5.1 UNAVAILABILITY OF A VERTICAL SPILLWAY GATE

In this section, a single vertical lift gate is modeled and the unavailability of the system is evaluated as a function of time throughout its lifecycle. The vertical lift gate in this study is equipped with a drum and cable lifting mechanism and a single emergency power generator. It is assumed that the emergency generator and lubricants are inspected and tested every one and three months respectively. Heating elements of the gates are tested during yearly pre-winter tests. Also, three major types of tests are performed to ensure the availability of the system: partial gate lift test (10% lift), full opening with stoplogs, and full gate lift under full hydro-static load. These are assumed to be conducted regularly at intervals of 2, 5 and 15 years respectively. Maintenance and inspection procedures are assumed to be performed in accordance with specifications from component manufacturers.

For this study, it is assumed that electrical components have constant failure rates and are modeled using the exponential distribution, mechanical and structural components experience aging and deterioration and are therefore modeled with time-dependent hazard rate functions using the semi-Markov analysis as discussed in section 5.3.2. Parameters of the Weibull and exponential distributions are obtained from sources such as USACE (2001). A list of failure rates associated with spillway gate components may be found in Appendix C. A duty factor (the ratio of operating time over total time) is considered for each component as well as K-factors to account for the environmental conditions. Inspections/test frequencies and efficiencies are also added to each component individually. Figure 5-3 shows the unavailability diagram of the vertical lift gate system.

It is important to note that in this study, most failed component are restored to conditions before failure (as good as old) after the end of a dormant interval and there is no component replacement until the component reaches a predefined unavailability limit after which it is replaced with a new component. Also, it is assumed for our purposes that the 10% gate lift test (performed every two years) has an efficiency of varying between 80 to100% for the electrical and mechanical subsystems. However, this test has an efficiency of less than 40% for the structural subsystem. The stoplog test (performed every 5 years) also has efficiencies between 30 to 40% for most mechanical and electrical components and between 70 to 100% for structural components.

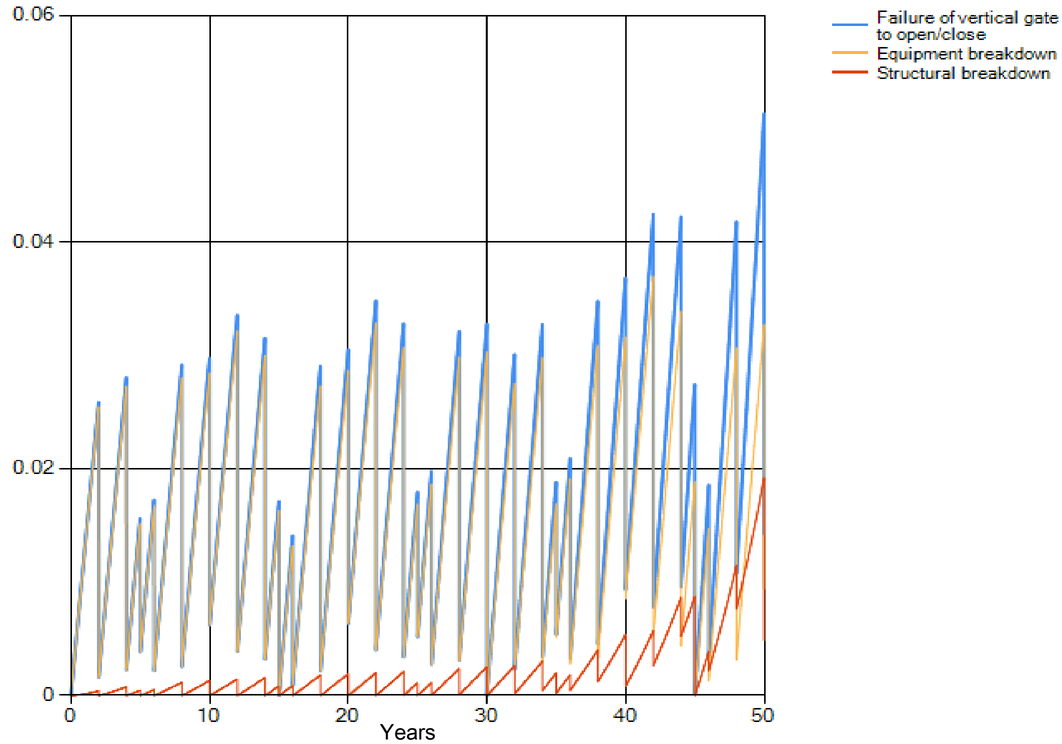


Figure 5-3: Unavailability of the vertical gate and of the equipment and structural subsystems

5.5.2 LOAD REJECTION

Load rejection occurs when the distribution grid fails to accept the electrical load from the turbine-generator system which must be shut down to prevent damage to the equipment (Çalamak, et al., 2012). With the shutdown, the level of water can rise quickly for run-of-the-river dams and result in overtopping of the dam. Load rejection may happen at any time, therefore, spillway gate systems of hydroelectric dams must be able to respond on demand to release flow equivalent to the turbine flow and maintain water levels at normal operating conditions.

For a vertical spillway gate system with four gates, a single gate is usually sufficient to release the excess flow of water due to load rejection. The unavailability of the spillway gate system during load rejection is determined in the following sections for both individual and common lifting mechanisms.

5.5.2.1. INDIVIDUAL LIFTING MECHANISM

It is assumed that all four gates are heated (can be operated during summer and winter), remote controlled, and have individual lifting mechanisms. To consider the most critical scenario, it is assumed that load rejection occurs during winter which requires the use of heaters. The spillway gate system has four gates in redundancy, opening any one gate out of four is sufficient to successfully pass the excess water due to load rejection. Using the fault tree model of the software application, the spillway gate system can be modeled with four redundant gates (in parallel) including all electrical, mechanical and structural components related to each gate as illustrated in Figure 5-3 As shown in this figure, the power system (central power and the emergency power generator is common between all four gates). Detailed branches of the tree are too large to be added in this article as they contain more than 40 components from the equipment and structural subsystems.

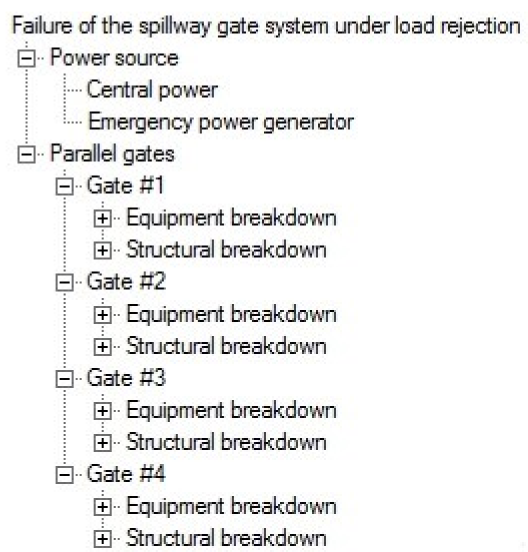


Figure 5-4: Tree view showing the four redundant gates of the vertical spillway gate system under the load rejection scenario

Figure 5-5 shows the unavailability of the spillway gate system to operate during load rejection using the software application.

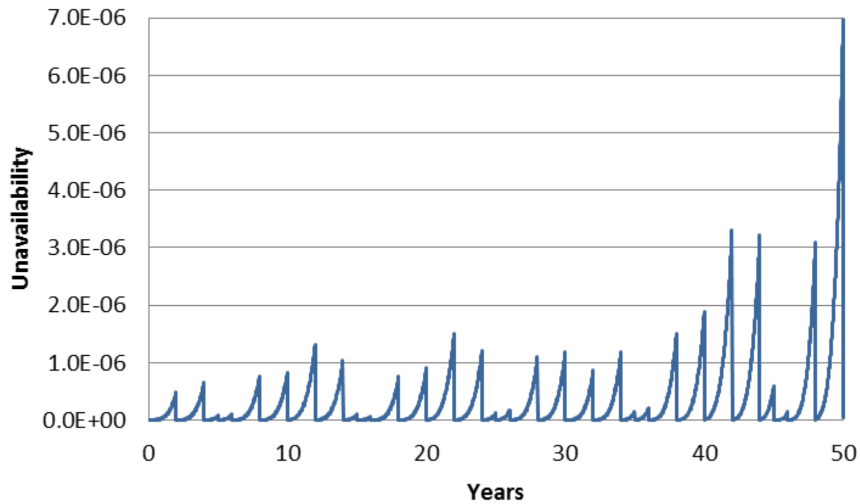


Figure 5-5: unavailability of the vertical spillway system with independent lifting mechanism -the load rejection scenario

The average unavailability of this spillway gate system during its 50 year service life and load rejection scenario is 3.28E-07 which is extremely small when compared to average unavailability value of a single gate which is 0.017 from the previous section. This is due to the redundancy of the four vertical gates of the spillway system. This example shows that redundancy plays a very important part in improving the availability of the system. Therefore, it is essential for dam owners to make sure that more than one gate is available to operate at any point in time, particularly for spillways which have non-heated and manually operated gates which are not operable at all times. The load rejection scenario is usually accompanied by problems with the distribution and transmission line which can also increase the likelihood of loss of central power. This event, although not considered in this example, can affect the failure probability of the power source.

5.5.2.2. COMMON LIFTING MECHANISM

As discussed earlier in section 5.5, the common lifting mechanism consists of a gantry crane with all lifting elements mounted on the mobile structure. The crane moves on carrying tracks from one gate to another with the use of a translation motor lifting the gates one at a time. Failure of the lifting mechanism is a common mode failure.

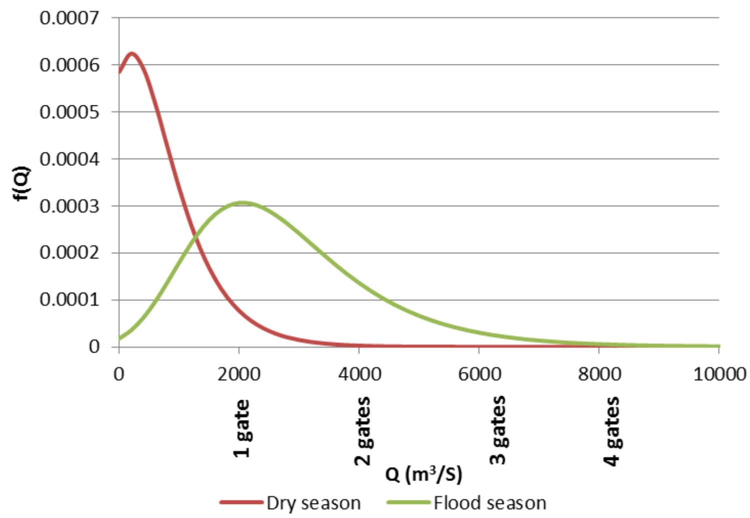
Assuming that opening one gate is adequate to release all excess water due to load rejection, a general policy from dam owners is to attach the gantry crane to one gate that is operated during load rejection. Under this assumption, the unavailability of the spillway gate system can be modeled as the unavailability of a single gate with an independent lifting mechanism.

5.5.3 FLOOD

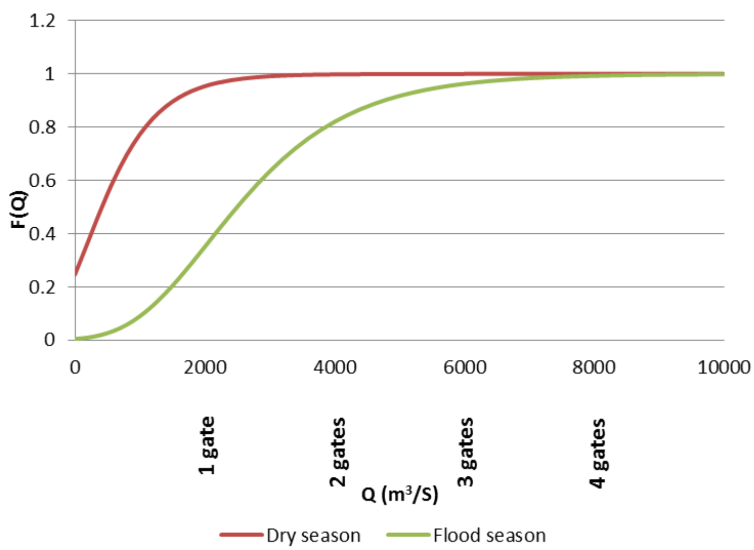
Flooding may occur due to river ice jam breakup or extreme precipitation. In order to avoid dam overtopping during a flood, one or multiple gates need to be opened depending on the discharge required. According to dam safety regulations of Quebec, dams classified in the high consequence category must be able to withstand a probable maximum flood (PMF) with a probability of exceedance of 10^{-4} (2013).

Flood frequency analysis is used to support the design and operation of dams and spillways systems. It is generally outperformed by fitting peak flow observations to suitable probability distributions. Two of the main approaches include using an annual maximum series (AM) which considers the largest event in each year and a partial duration series (peak-over-threshold method -POT) which considers all flows above a given threshold (Baratti, et al., 2012). Seasonal flood frequency distributions can be used by dam owners for planning of inspections and tests prior to periods of the year with higher probabilities of flood flows. Analyses of seasonality of flood frequency are strongly related to seasonal variability of rainfall and snowmelt (Kochanek, et al., 2012) (Tao, et al., 2002).

For this case study, it is assumed that two seasons exist in a hydrological year: a wet season and a dry season. It is also assumed that the Generalized Extreme Value Type I (Gumbel) distribution is appropriate for the seasonal flood frequency distribution. Figure 5-6(a) and (b) show the PDF and CDF of the assumed seasonal flood frequency distribution for the dry and wet season.



(a)



(b)

Figure 5-6: Seasonal flood frequency distribution, Gumbel $\boldsymbol{\alpha_{Wet} = 5700}$, $\boldsymbol{\beta_{Wet} = 1050}$, $\boldsymbol{\alpha_{Dry} = 2250}$, $\boldsymbol{\beta_{Dry} = 767}$ (a) PDF, (b) CDF

Assuming that each of the four gates have a discharge capacity of 2000 $m^3/_s$, Figure 5-6 also shows the number of gates required to control increasing levels of discharges during each season. This distribution is used to determine the availability of the vertical spillway gate system for flood scenarios of increasing severity with both independent and common lifting mechanisms.

5.5.3.1 INDEPENDENT LIFTING MECHANISM

As mentioned in section 5.5.2.1, for this scenario, it is assumed that all four gates of the spillway system are heated (can be operated throughout the year), remote controlled, and have individual lifting mechanisms. The number of gates required at any moment is a function of the flow which affects the availability of the spillway. For example, for a flood with a discharge rate of up to 4000 $m^3/_s$' any two out of four gates can be used.

Figure 5-7 shows the average and the maximum point unavailability of the spillway gate system as a function of the flood discharge ranging from minor flooding to the PMF (here assumed 10^{-4}). The maximum point availability value corresponds to the worst case scenario throughout the service life of the spillway.

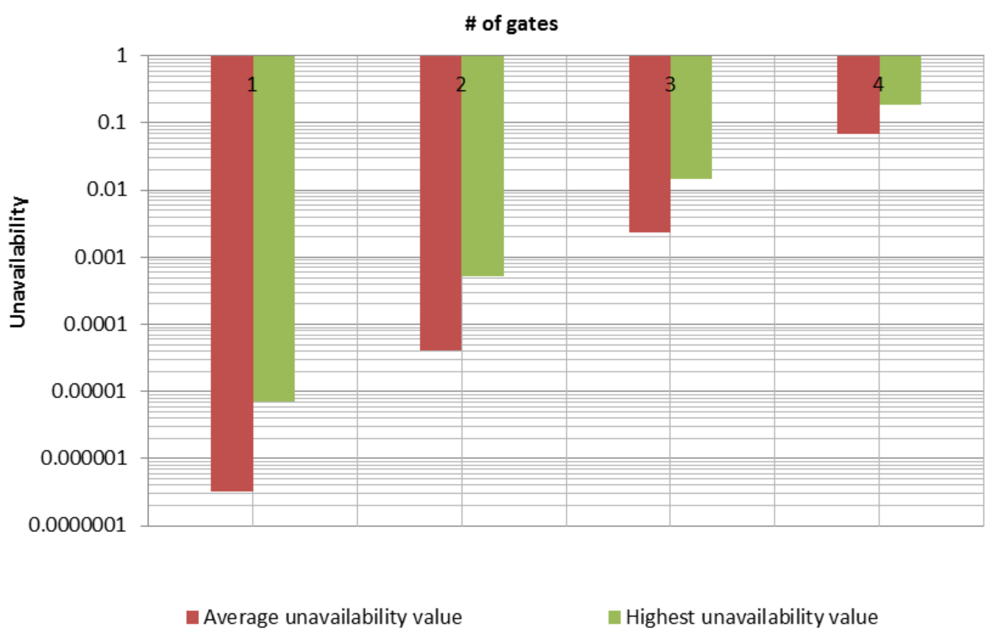


Figure 5-7: Average and maximum point unavailability of vertical spillway gate system with independent lifting mechanism- flood scenario

As illustrated in this figure, the unavailability of the spillway gate system to pass a flood of up to 2000 $m^3/_s$ which requires one gate to open is very low as only one out of four gates need to operate to pass the flood. For the PMF however, the unavailability increases significantly as all four gates need to function to pass the design flood.

Given the unavailability of the spillway gate system as a function of flood level, the probability of exceedance of the flood levels can be combined with availability to determine the annual probability of failure due to a flood event. Equation 5-4 is the probability of failure of spillway system for a flood scenario:

$$P[failure] = \sum_{i=1}^{N_{gates}} P[failure \mid fl_{i-1} \le FL \le fl_i] \cdot \left(F_{FL}(fl_i) - F_{FL}(fl_{i-1})\right) \qquad [5\text{-}4]$$

where fl_i is the flow capacity of *i* number of gates and FL is the flow capacity at a given level. Figure 5-8 shows the spillway system unavailability as a function of flood intensity for the wet and dry seasons. This figure shows that the probability of spillway gate system unavailability is very low in the dry season for floods which require the operation of more than one gate due to the low probability of occurrence of high intensity floods. For the wet season, the probability of floods of up to $6000\ {m^3}/{s}$ (requiring three gates) are quite high and when combined with spillway gate system unavailability create a high probability of system failure during flood. For floods of more than $6000\ {m^3}/{s}$ and close to the PMF the occurrence probability of floods is reduced significantly causing a decline in the joint probability.

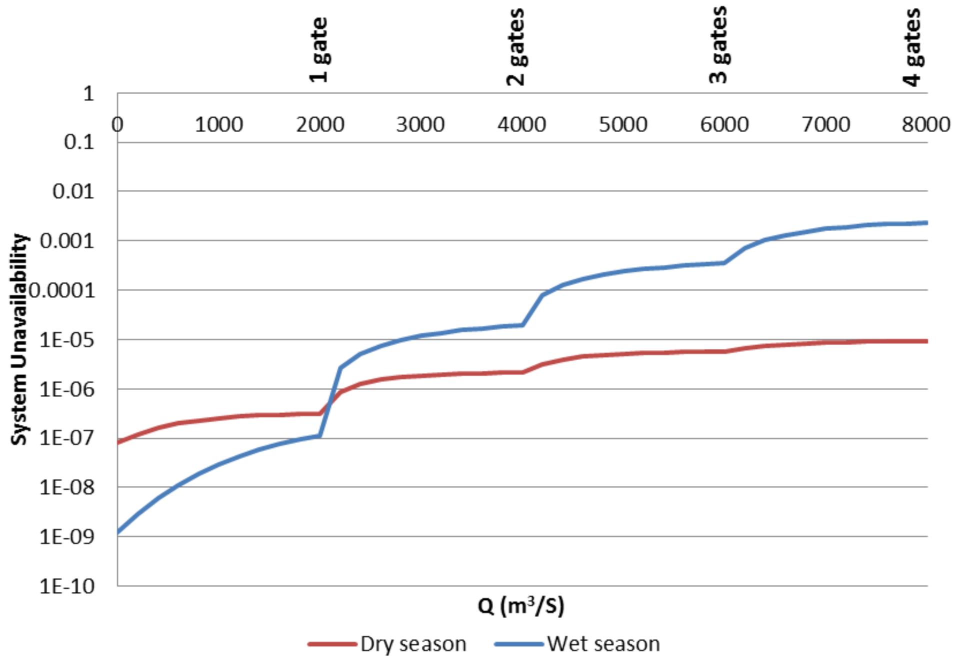


Figure 5-8: Joint probability of spillway gate failure and flood for the wet and dry seasons (independent lifting mechanism)

This information can assist dam owners in determining strategic inspection and testing schedules. The results show that the probability of flooding during the dry season is very small, therefore it is more advantageous to plan yearly inspections and tests at the start of the wet season to ensure all potential issues are resolved and gates are operable on demand. Application of efficient inspection and tests at the start of the wet season can greatly reduce the unavailability of the spillway gate system and the risk associated with its failure.

5.5.3.2 COMMON LIFTING MECHANISM

The spillway gate system with a common lifting mechanism is only capable of opening each of the four gates one at a time and failure of the gantry crane and common lifting elements will lead to the failure of the remaining unopened gates. Figure 5-9 shows the average and the highest unavailability values of a spillway gate system with four vertical gates and a common lifting mechanism. As illustrated in this figure, since the lifting mechanism is usually installed on one of the gates (designated for operation during load rejection) the average unavailability of opening one gate to pass the flood is the same as the unavailability associated with the load rejection scenario with one gate. However, for operating more than one gate, the lifting mechanism is a common mode of failure and there is an increase in the average unavailability relative to gates with independent lifting mechanisms. The relatively small increase in average unavailability between two and three gates is due to the fact that the common lifting mechanism and the power supply are the controlling elements in spillway system unavailability and their unavailability dominates over the effects of adding one gate. Overall results show a significant increase in the unavailability relative to the spillway system with independent lifting mechanisms for each gate.

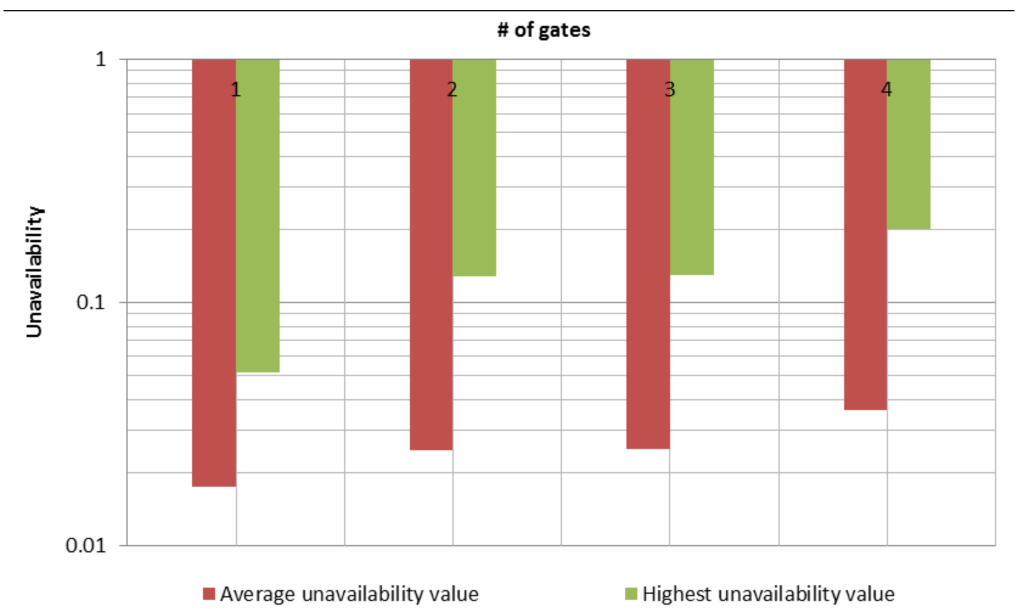


Figure 5-9: Average and highest point unavailability values of a spillway gate system with a common lifting mechanism

Next, the effect of adding the flood frequency CDF to the unavailability of the spillway gate system is investigated. Figure 5-10 shows the joint probability of flood and spillway gate unavailability for both wet and dry seasons.

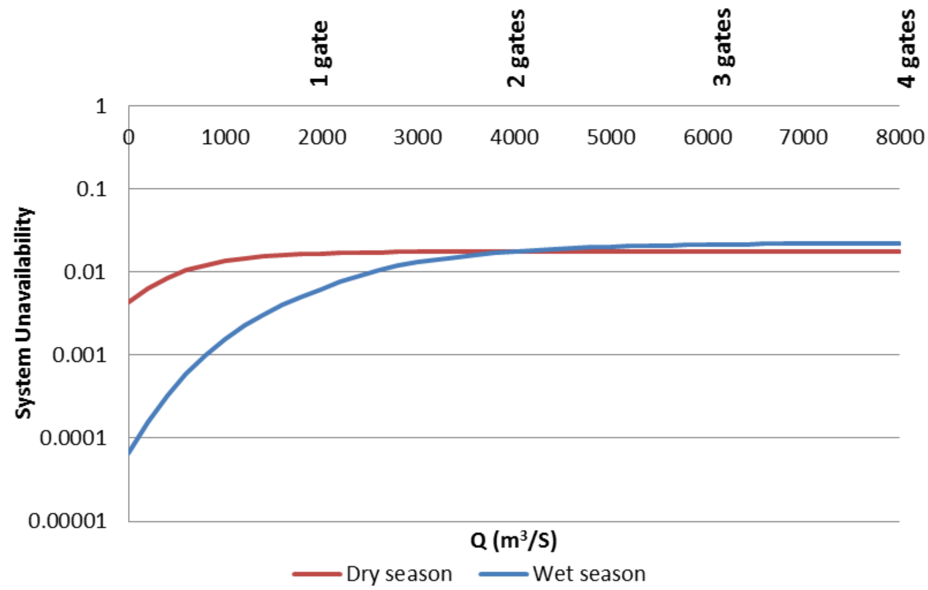


Figure 5-10: Joint probability of spillway gate system failure and flood for the wet and dry seasons (common lifting mechanism)

This figure shows that the unavailability is much higher relative to the independent lift for spillway system with common lifting mechanism in both wet and dry seasons. In the dry season the probability stabilizes for discharges requiring more than one gate. In the wet season also, the unavailability remains stable up to floods relatively close to the PMF. The increase in the joint probability between common and independent lifting mechanisms shows the criticality of spillways systems with common lifts. Therefore, it is essential for dam owners to conduct effective inspections and tests on the gantry crane and the lifting equipment on both wet and dry seasons. Inspections/tests on other gate components is best conducted at the start of the wet season to reduce unavailability for that period where there is probability of larger floods requiring operation of more than one gate.

5.6 OPTIMIZATION OF INSPECTION AND TESTING STRATEGIES

Inspections/tests may have different effects on components of the spillway gate system and very high efficiency tests are not always economically feasible to perform. Therefore, an optimum inspection/testing strategy is required to determine the optimum frequency of inspections/tests using parameters such as efficiency, cost of inspection/test and consequence of failure. Many studies have been conducted in this area; Kancev and Cepin (2011) investigate how costs and component aging affect the testing and maintenance optimization in terms of minimal system risk. Barroeta and Modarres (2005) studied the optimal inspection policy for periodically tested, repairable components undergoing an aging process and Hontelez et al. (1996) have developed optimum condition-based maintenance policies for deteriorating systems to develop the optimum inspection/testing plan. Most methods minimize a cost function in order to obtain the optimum frequency of inspections/tests. In this approach it is important to take into account all costs such as costs of performing inspections/testing, cost of repair and consequences of failure (Ahmadi, et al., 2011) and (Vaurio, 1995).

In this application, the optimum inspection/testing intervals is determined for a given spillway gate system by minimizing the following cost function:

$$Z(T) = SL\sum_{i=1}^{n} {C_i}/{T_i} + C_F UA_{avg} \quad [5\text{-}5]$$

where n is the number of inspections/tests being optimized, C_i is the cost associated with the inspection/test of type i, T_i is the time interval between inspection/test of type i, SL is the service life of the spillway gate system, C_F is the cost of failure and UA_{avg} is the average unavailability of the spillway gate system during the service life. This cost function is minimized with the constraint that the average unavailability of the spillway gate system remains below the unavailability limit defined by dam owners based on existing standards and classifications:

$$UA_{avg} \leq UA_{limit} \quad [5\text{-}6]$$

Combining Equations 5-5 and 5-6 creates a constrained nonlinear optimization problem in which neither the objective nor the constraint functions are necessarily twice differentiable. Therefore, this problem cannot be solved using conventional optimization techniques such as the Golden Section approach. Methods such as genetic algorithm (GA), simulated annealing (SA) and random search (RS) are generally used to solve non-differentiable, discontinuous optimization problems with highly nonlinear objective and constraint functions (Yeniay, 2005).

The optimization procedure adopted to determine the optimum frequency of inspection/testing for a combination of inspection/test types is genetic algorithm. The following section gives a brief overview of the genetic algorithm technique.

5.6.1 GENETIC ALGORITHM

Genetic algorithm is an optimization procedure based on principles of evolution observed in nature. This approach imitates the evolution of living beings described by Darwin as survival of the fittest. The algorithm uses three main principles of the natural evolution: reproduction, natural selection and diversity of the species (Poppov, 2005). The flow chart of a typical genetic algorithm is shown in Figure 5-11.

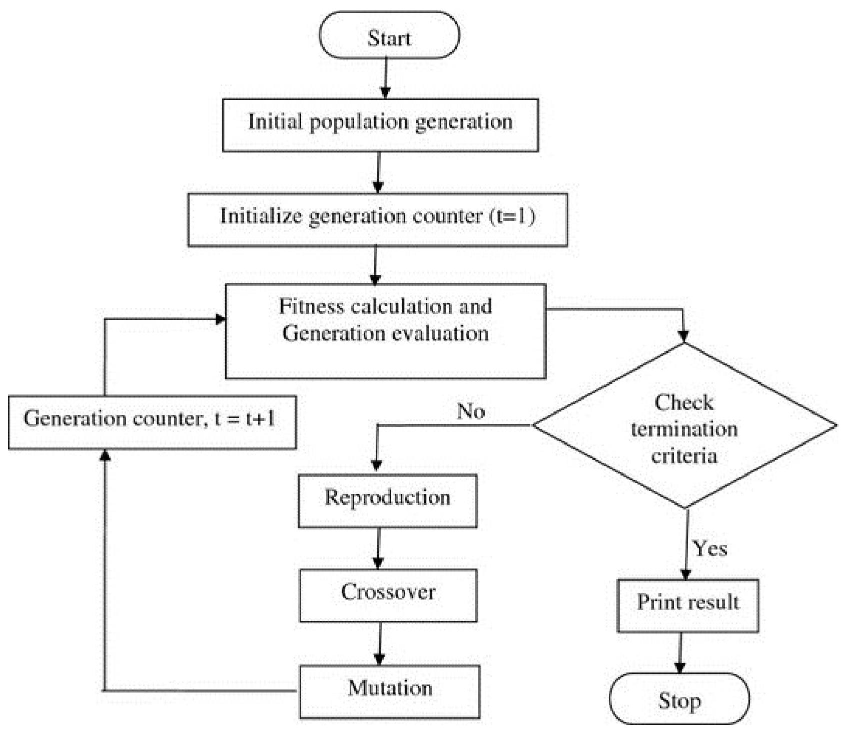


Figure 5-11: Flow chart of a typical genetic algorithm technique (Tewari, et al., 2012)

The genetic algorithm approach can be summarized by the following steps:

1) The program starts by generating an initial population of possible solutions (chromosomes) randomly. Each chromosome consists of the intervals of the inspections/tests being optimized transformed into binary form using Equation 5-7 and 5-8.

$$T_i = Rand(\,) \times SL \qquad [5\text{-}7]$$

$$(T_i)_{10} \rightarrow (T_i)_2 \qquad [5\text{-}8]$$

where T_i is the interval of the i^{th} test, $Rand(\,)$ is the random number generator function and SL is the service lift of the system. After each test interval has been created randomly, it is then transformed into its binary form.

2) The solutions are assessed using a fitness function and the fittest solutions are identified. The fitness function used by the program is the cost function of Equation 5.2.

3) A sample of solutions is then selected from the initial population for crossover (mating). The program uses the roulette wheel concept to select the sample which gives more weight to fittest solutions. The roulette wheel selection method is conceptually equivalent to giving each individual a slice of a circular roulette wheel equal in area to the individual's fitness. The roulette wheel is spun, the ball comes to rest on one wedge–shaped slice, and the corresponding individual is selected (Mitchel, 1999)

4) Selected solutions are placed in the gene pool for cross-over to create new offspring solutions. In the cross-over process the two test intervals (one from each solution) in their binary form are placed over each other and a cutting point is selected randomly along the length of the binary strings. After the cut, the remaining fragments on the right of the cutting point are interchanged creating two new chromosomes as shown in the following example in Figure 5-12.

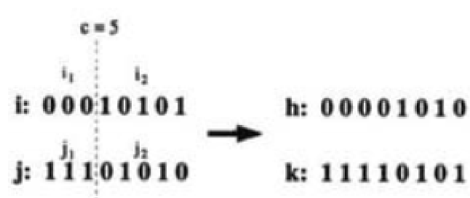


Figure 5-12: Example of crossover (mating) (Mitchel, 1999)

5) From the offspring solutions, a small percentage is selected for mutation. During the mutation process, a randomly selected digit of the binary string of a new test interval is selected. If the value of the digit is one it is switch to zero and vice versa.

6) This sample is now formed of the new generation of solutions, steps 2 to 5 are then repeated until a predefined condition is satisfied. In this case, the algorithm terminates when the rate of change of the cost function is less than a predefined value for three consecutive generations.

The result of the optimization is shown as optimum intervals for each of the selected tests in days and the minimum cost associated with these intervals.

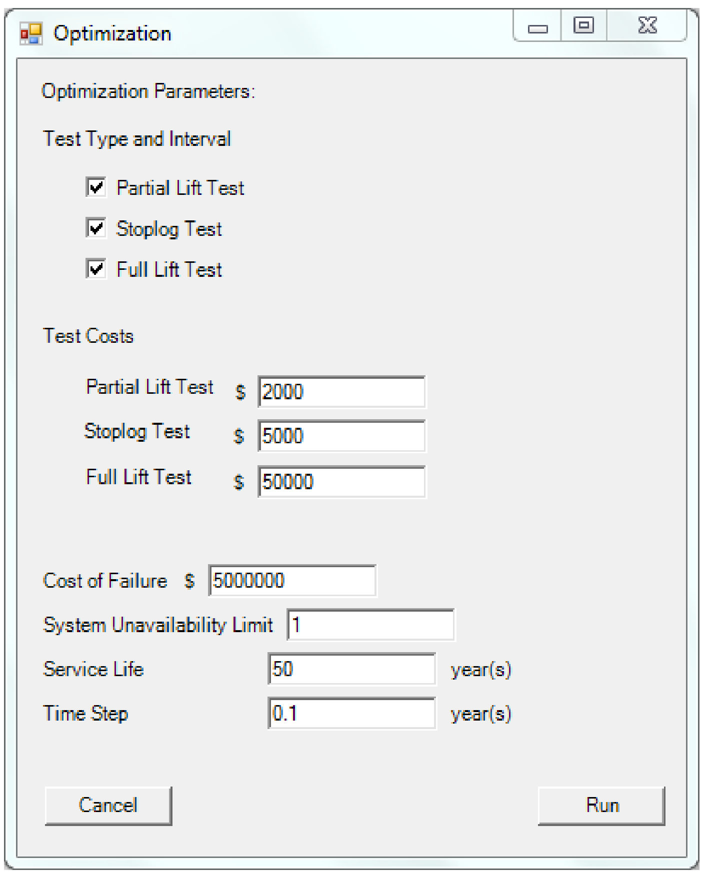


Figure 5-13: optimization dialog box of the software application

The optimization procedure is demonstrated for the vertical spillway gate system cases study. Figure 5-13 shows the optimization dialog box of the software application. It is assumed that all three types of tests are applied to the system. Also it is assumed that the cost associated with the partial lift, stoplog and full lift tests are \$2,000, \$5,000 and \$50,000 respectively. Similarly, the cost of spillway gate failure is assumed to be \$5,000,000. For this example, no unavailability limit has been assigned to the spillway gate system that is why it is set as "1" in the dialog box. The result of the optimization for a service life of 50 years is shown below:

$T1 = 338\ days$ (~1 per year)

$T2 = 1774\ days$ (~ 1 per 4.8 years)

$T3 = 4126\ days$ (~ 1 per 11.3 years)

$Cost = \$1{,}197{,}286$

where, T_1 is the interval between the partial lift tests, T_2 is the interval between the stoplog tests and T_3 represents the intervals between the full gate lift tests. As illustrated the optimum test strategy would be to conduct the partial test approximately every year, the stoplog every 5 years and the full gate lift every 11 years. With the optimum testing intervals defined, the average annual cost of testing is approximately \$7000.

In order to validate the results of the Genetic algorithm approach, the same scenario is optimized using the Creeping Random Search (CRS) method. The Random Search method consists of measuring the cost function at N random points selected from a probability distribution uniform over the entire parameter space and taking the smallest value as the minimum (Brooks, 1958). This requires a large number of trials which may be time consuming. The Creeping Random Search method generates random points in the first trial and starting from these base points the cost function is measured at a predefined step size at a random direction. If the cost function at the new point is less than the base point, the base point is moved to the new point. This is continued until moving a step size in any direction will not yield a smaller cost value. (White, 1970). The results of the same model optimized using this approach is shown below:

$T1 = 343\ days$

$T2 = 1659\ days$

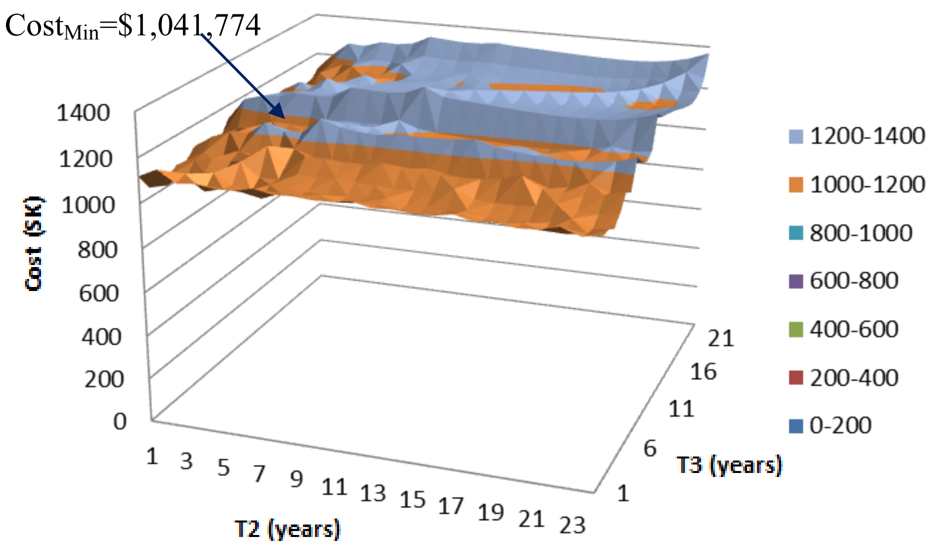
$T3 = 4115\ days$

$Cost = \$1{,}156{,}112$

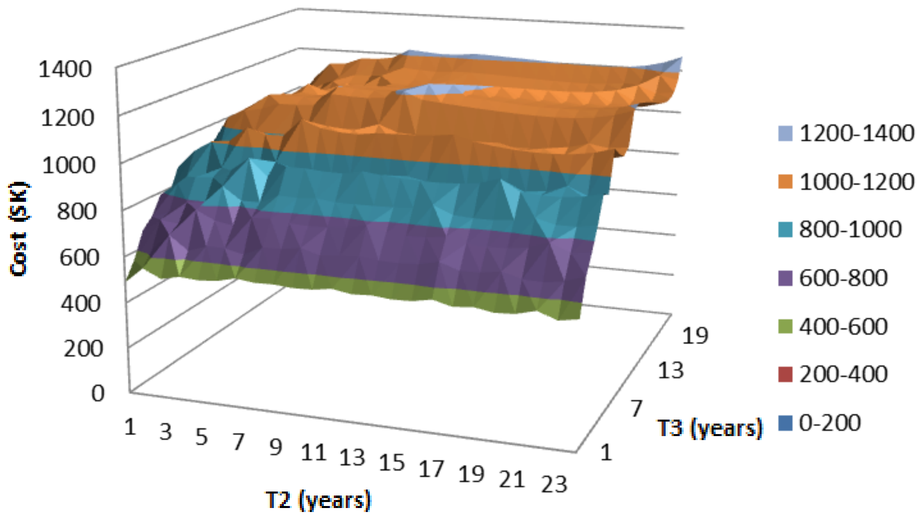
The similarity of results between the two approaches confirms that the selected test intervals are optimum values in terms of cost which also maintain the unavailability of the system below the defined limit.

To better demonstrate the shape of the optimization function, Figure 5-14(a) shows the cost function in thousand dollars by assuming that partial lift test are fixed at one year intervals throughout the life of the system. As illustrated, the three-dimensional surface of the cost function is the sum of the maintenance costs, Figure 5-14(b), and cost of failure, Figure 5-14(c).

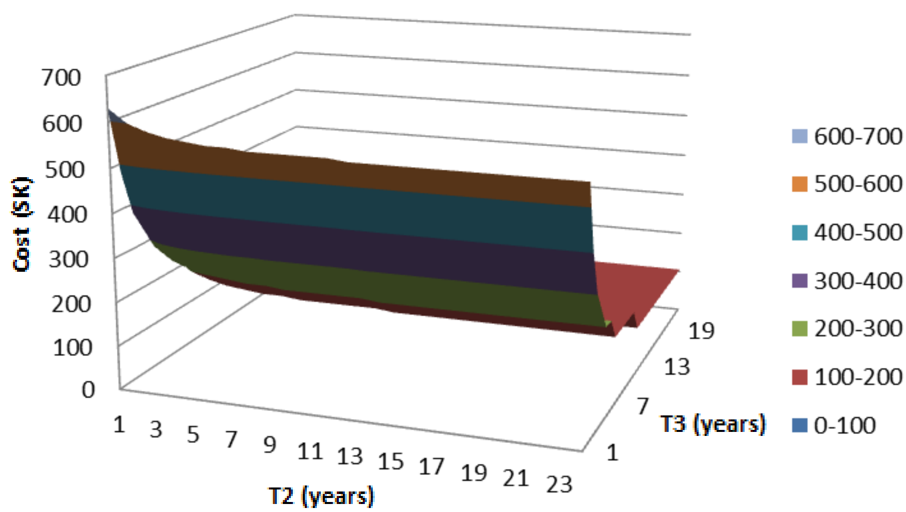
Optimum point: T_2=5 years, T_3=11 years



(a)



(b)



(c)

Figure 5-14: (a) Cost function surface, T_1=1 year, (b) Cost of failure (second term of Equation 5-5), (c) Cost of testing (first term of Equation 5-5)

High capacity spillway gate systems such as the example in this article have catastrophic failure consequences; therefore, in order to minimize the cost function the second term of Equation 5-5 has to be kept as small as possible requiring the average unavailability of the system to be very small. Hence for large dams, the optimization function itself promotes the selection of test strategies that reduce the average unavailability as much as possible. For smaller dams with low consequences of failure however, the first term of Equation 5-5 takes over and consequently, the scenario with the least amount of tests and therefore test costs will be selected as optimum. This effect is shown in Figure 5-15 which illustrates the trend of optimum test intervals as a function of dam classification (consequence of dam failure). Failure consequence values associated with each dam class have been obtained from the Dam Failure Consequence Classification Conversion Guideline for Dams in British Columbia (BC Reg. 163/2011, 2011).

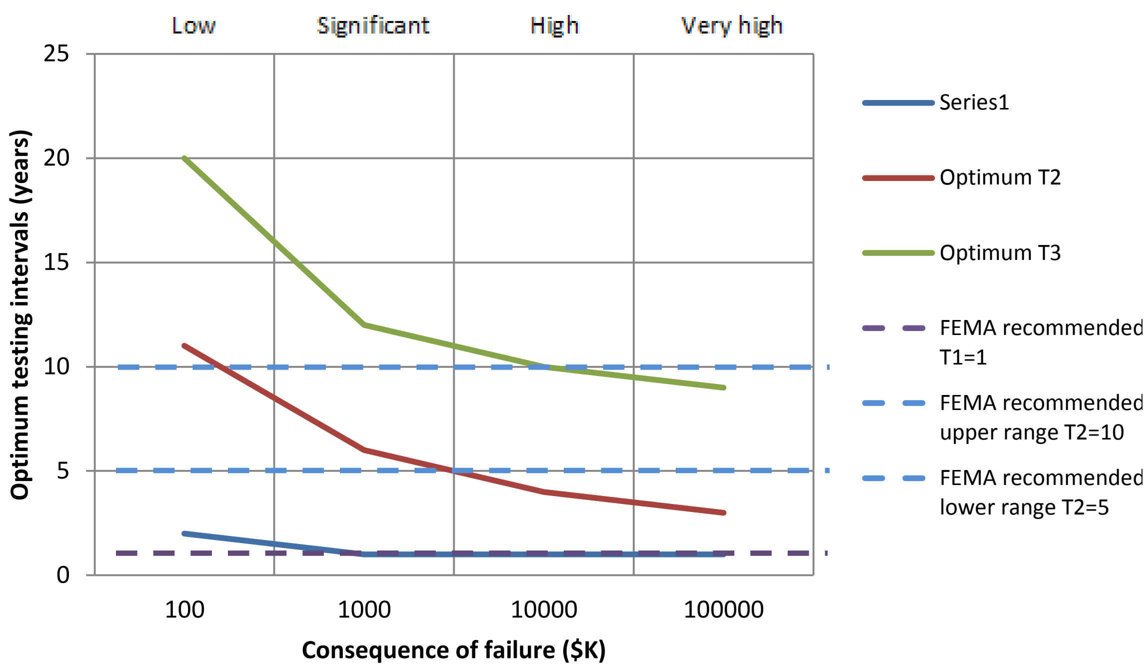


Figure 5-15: Optimum testing intervals as a function of dam classifications

To avoid high unavailability values it is best to designate an unavailability limit beyond which the unavailability of the system in unacceptable. By adding this constraint to the optimization problem, the optimum test intervals are determined such that the average unavailability of the system remains under the defined limit. To demonstrate the effect of unavailability limit for low consequence dams, the above case study has been repeated by reducing the failure consequence of the system to $500,000 and for an unavailability limit of 10%. The results from the Genetic Algorithm approach are shown below:

$T1 = 444\ days$ (~1 per year)

$T2 = 2923\ days$ (~1 per 8 years)

$T3 = 6893\ days$ (~1 per 18 years)

$Cost = \$214{,}914$

$Average\ Annual\ cost\ of\ tests = \$4600$

5.7 SUMMARY OF RESULTS AND DISCUSSIONS

This paper demonstrates the abilities of a software application developed in the Civil Engineering department of McGill University for spillway reliability analysis. The purpose of this study was to evaluate the effect of inspection/test type and frequency on the availability of spillways gate components and system as a whole. The first objective of this paper was to determine the effect of type and frequency of inspection/test on the availability of the electrical and mechanical components of the gate. The largest intervals between inspections/tests were also determined using the maximum allowable unavailability value of a component based on dam classifications or standards defined by dam owners. The results highlight the importance of performing inspections/tests which have high failure detection efficiencies for each component type. Inspections/tests with higher efficiencies contribute more to reducing component unavailability and therefore, require fewer inspections/tests to remain within acceptable unavailability limits. If inspections/tests are inefficient, more tests are required to maintain component unavailability within the same limits.

The second objective of this article was to investigate the availability of a spillway gate system comprised of a combination of gates under load rejection and flood scenarios. These two scenarios were investigated for systems with both individual and common lifting mechanisms. The case study determined the average and point unavailability of the system for a given inspection/testing strategy for each scenario. Using the software application, dam owners will be able to determine the unavailability of their spillway gate system during flood and load rejection and establish whether or not the strategy adequately maintains the unavailability values under the limit defined by the dam classifications. In the load rejection scenario, gates with independent lifting mechanisms act as parallel systems. In other words, while some gates have priority of opening over others, opening any gate will pass the excess water due to load rejection. For common lifting mechanisms, as demonstrated in the case study, the lifting mechanism is usually locked to one of the gates designated for load rejection; therefore, only one gate can function during this scenario.

During the flood scenario, depending on the flood discharge one or a number of gates need to open to pass the required amount of water. The spillway gate system will have higher unavailability values for larger floods which require more than one gate to operate at the same time; therefore it is essential to identify seasonal and annual flood frequencies in the area and to ensure the system is inspected/tested efficiently and has the required availability prior to the flood season.

The last part of this article determines the optimum inspection/testing strategy for spillway gate systems. This is done by minimizing a cost function comprised of inspection/test costs and costs related to failure consequences. In this section, optimization is done using the software application incorporating both the Genetic Algorithm and the Creeping Random Search approach as two comparative methods to ensure the accuracy of results. The results show that for high consequence dams, the optimum test strategy is one which minimizes the average unavailability of the system while in lower consequence dams, the optimum strategy would be one with fewer number of tests and therefore lower test costs, therefore, introducing an unavailability limit for such systems would ensure that the unavailability of the spillway gate system remains within an acceptable range even if lower costs are achievable.

5.8 CONCLUSION

The first objective of this study was to demonstrate the abilities of the software application developed at McGill University to investigate the effects of type and frequency of inspection and testing on components of a spillway gate system as well as the system as a whole. Spillway gates are usually dormant and are located in remote areas and subjected to severe environmental conditions. This study finds that both the efficiency and the frequency of inspection/testing can significantly affect the reliability of the gates. It is important to recognize that the efficiency of a given test to detect failure may be different from one component to another. The second objective was to determine the unavailability of the spillway gate system during failure scenarios of flood and load rejection. The results show that gates with common lifting mechanisms have a higher unavailability and therefore require more rigorous inspection/testing and monitoring particularly prior to flood/wet seasons. Finally, the paper also determines the optimum inspection/test strategy both in terms of cost and unavailability. The optimization problem solved by both Genetic Algorithm and Creeping Random Search approach illustrates how the optimization approach varies for different dam classifications.

This article has introduced the newly developed software application and the methodology to determine component and system unavailability and to evaluate the effects of type and frequency of inspections and tests on the availability of spillway gate systems. This is essential to dam owners in developing an optimum inspection and testing strategy based on dam classifications. For a specific dam classification an optimum inspection and testing strategy will ensure that spillways gate system reliability meets the classification requirements and at the same time reduces or eliminates costly inspections/tests which contribute little to the performance of the system.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Dams are essential infrastructures for society. The main purposes of dam construction include water supply, hydropower, flood control, irrigation, and navigation. Possible events that could initiate a dam failure consist of external event such as excessive static or dynamic reservoir loads, floods, upstream dam failure and earthquakes and internal events such as structural deterioration, foundation weakening, seepage and erosion, mechanical or electrical failure of spillway and operator error. Out of these only a few initiating failures are dominant contributors to risk. These dominant modes of failures vary depending on type of dam (i.e., earth dam, concrete dam), storage type (reservoir or run of the river dams), dam capacity, etc.

Maintaining the safety of aging infrastructures is a major concern of owners and operators. Dams are no exception to this dilemma. Spillways are critical component of a dam which, by controlling releases, prevent overtopping and reduce impacts associated with excessive downstream flows and upstream water level, on infrastructures, the population and the environment. Spillway gate systems are among the most crucial for maintaining the safety of a dam and require assessments of both equipment and operational failure modes. Statistics and the aging state of current dams indicate that spillways are becoming more prone to failure. As the consequences of dam failure can be catastrophic and could involve loss of life, it is critical to develop procedures to evaluate the reliability and risk associated with spillways and to develop mitigation procedures that may also include warning systems in the event of a possible flood inundation due to a dam breach. Also, empirical evidence demonstrates that the perceived level of reliability of gates overestimates the actual reliability, especially for gates that are operated very infrequently.

Components of most spillway gate systems spend the majority of their service life in a dormant state and are activated randomly (i.e. for high flows or load rejection) or on a regular basis for inspection and testing. Also, most spillways are located in remote areas and are subjected to severe environmental conditions which can cause early degradation of components. Furthermore, components of old spillway gate systems are often custom made with no readily available spare parts and little information on the reliability of the existing component. These characteristics make it difficult for traditional methods to deliver accurate estimates on the reliability of such systems. Therefore, a new method is required to take into account all the unique characteristics of the spillway systems as well as the effect of type and frequency of inspections and tests to accurately determine system availability on demand and considering different failure scenarios.

In this study, a novel methodology as well as the related software application is developed to accurately determine the availability of spillway gate systems. Initially, an updating mechanism is developed to determine the real time availability of components based on their condition after each inspection. The dormant condition indexing approach accommodates degrading and aging of the system as well as component dormancy. This approach provides a tool for dam owners to detect real time changes in the availability of spillway gate systems.

Next, Markov/semi-Markov analysis is used to model electrical, mechanical and structural components and latent failures during dormancy. K-factors and duty cycle factors are also used to incorporate environmental conditions and the effect of dormancy respectively. Fault tree analysis is then used to model the spillway gate system and component interactions. The effect of inspections and tests on the availability of spillway gate system is determined in order to identify the most effective inspection and testing plan both in terms of cost and increase in system availability. Over time, even with regular inspection and maintenance, the dormant nature of the system along with the severe environmental conditions to which spillways are exposed, may result in the degradation of performance of components. Therefore, testing the functionality of the gate is an important aspect in ensuring continuous safe operation.

Finally, the optimum inspection and testing plan is determined for the spillway gate system which minimizes system costs including costs related to inspection and testing as well the consequences of failure while at the same time maintaining the availability of the spillway gate system above a predefined limit. The main approach used to solve this optimization problem is Genetic Algorithm through which the cost function is minimized with the availability limit as a constraint. The results from this approach are then validated using the Creeping Random Search Method.

A software application is then developed using Visual Studio® 2012 and the methodology is integrated into a user friendly program with a strong user interface. With this software application, users will be able to model a spillway gate system comprised of electrical, mechanical and structural components, add dormancy, environmental effects and inspection and test options to each component and determine the availability of each component as well as the entire system as a function of time. Also the software application has a built in optimization option and the optimum inspection/testing plan for the modeled spillway and minimum system costs can be determined by adding inspection/testing costs and failure consequences.

Using the software application dam owners will be able to determine the unavailability of spillway gate systems for potential failure modes such as flood and load rejection and establish whether or not the existing maintenance, inspection and testing strategy adequately maintains the unavailability values below the limit defined by the dam classifications.

Case studies have been conducted for a spillway with four vertical lift gates both with independent and common lifting mechanisms. The unavailability of each component and the gate assembly has been determined as a function of time based on specific inspection and testing strategies. The unavailability of the entire spillway (all four gates) has also been investigated for the two most common failure modes of load rejection and flooding. For the load rejection scenario, results from the software application indicate that gates with independent lifting mechanisms have lower unavailability values since the four gates act as a parallel system. In other words, while some gates have priority of opening over others, opening any gate will pass the excess water due to load rejection. For common lifting mechanisms, the lifting mechanism is usually locked to one of the gates designated for load rejection; therefore, only one gate can function during this scenario leading to higher system unavailability.

During the flood scenario, depending on the flood discharge one or a number of gates need to open to pass the required amount of water. Here, the spillway system with a common lifting mechanism also has higher unavailability since the lifting mechanism acts as a common mode of failure as its failure will cause failure of all four gates to operate. Also, spillway gate systems will have higher unavailability values for larger floods which require more than one gate to operate at the same time; therefore it is essential to identify seasonal and annual flood frequencies in the area and the ensure the system is inspected/tested efficiently and has the required availability prior to the flood season.

Case studies also include optimization of inspection/testing strategies for spillway gate systems. This is done by minimizing a cost function comprised of inspection/test costs and costs related to failure consequences. Here, optimization is conducted using the software application incorporating both Genetic Algorithm and the Creeping Random Search approach as two comparative methods to ensure the accuracy of results. The results show that for high consequence dams, the optimum test strategy is one which minimizes the average unavailability of the system while in lower consequence dams, the optimum strategy would be one with fewer number of tests and therefore lower test costs. Therefore, introducing an unavailability limit for such systems would ensure that the unavailability of the spillway gate system remains within an acceptable range even if lower costs are achievable.

The novel approach and software application can contribute greatly to the dam industry by accurately determining the availability of the spillway gate system and its components as a function of time and for potential failure modes, evaluating the effects of different inspection and testing strategies on system availability and determining the optimum inspection/testing plan for a given spillway.

6.1 STATEMENT OF ORIGINALITY

The original contributions of this research project are summarized as follows:

- A novel dormant condition indexing approach combining Condition Indexing method and dormant availability analysis. In this approach a quantitative index is derived from qualitative and descriptive inspection results as a mean to determine the current state of the system and to project the condition of the system in the future. This method provides information on the current state of the system after each inspection takes place allowing dam owners to obtain real time updates on the availability of the system and to project its future conditions and to verify whether or not the behavior of the system is as expected.
- A novel approach in spillway reliability analysis by incorporating the effects of both type (efficiency) and frequency of inspections and tests in the availability

model. As the efficiency of a given inspection or test to detect failure may be different from one component to another, accounting for type and frequency of inspections/tests ensures more accurate availability results.

- A novel approach in the availability analysis of structural components. In this study, multi-state, semi-Markov analysis has been used for the first time for determining the availability of structural components of spillway gate systems. This model accounts for various aging and degrading states of a structural component as well as the effects of dormancy and environmental conditions.
- A novel system availability analysis program developed in Visual Studio specifically for the availability analysis of spillway gate systems incorporating, time-dependent failure probability distributions, Markov, semi-Markov and fault tree analysis, component environmental and dormancy conditions and optimization algorithms.

6.2 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

The dormant condition indexing method can be beneficial to the dam industry and at present, if conducted regularly throughout the lifetime of a system, as a comparative measure to identify changes in the condition of the system as it deteriorates; however, in order to use this approach independently to determine the availability of the system, more CI data is required to develop a connection between failure rates and the CIs as a calibration scheme. Therefore, the method needs to be added to the inspection procedure of spillway gate systems to be conducted regularly for a substantial period of time to acquire a comprehensive database of CIs relative to failure rates.

Other limitations in component and system modeling include limited sources of failure data for structural components, simplification of component interactions, correlations and the effect of cascading failures and not accounting for operational failures in the fault tree model.

For future work it is recommended to update inspection and testing procedures to collect data on CIs and structural failure rates in order to create a database for future references. It is also recommended to incorporate component interactions and correlations in the availability model. Furthermore, studying the operational aspect of spillway gate failure such as operator error, access to site and operational equipment and qualifications and training of operators may lead to a better understanding of gate operation and related failures. Finally, in the optimization approach, the consequences of failure are simplified and estimated as dollar value of damage to the dam, downstream population and the environment using an approach shown in Table 6-1.

Table 6-1: Consequence severity matrix (Developed with the feedback of loss prevention group of a major oil and gas company)

Severity Class	Asset Loss	Human Loss	Environmental Loss	Confidence or Reputation Loss
2	100K to 1 million	One or two injuries requiring hospital attention however no threat to life	Within plant, Short term remediation effort	Get attention in the industrial complex. Information shared with neighboring units
3	1 to 10 million	Multiple major injuries, potential disabilities, potential threat to life	Minor offsite impact, Remediation cost will be less than 1 million	Local media coverage
4	10 - 100 million	One fatality and/or multiple injuries with disabilities	Community advisory issued, Remediation cost remain below 10 million	Regional media coverage a brief note on national media
5	>100 million	Multiple fatalities	Community evacuation for longer period, Remediation cost in excess of 10 million	National media coverage, Brief note on international media

A more detailed investigation into human injury and loss of life, damage or destruction of downstream infrastructures and environmental and reputation loss can lead to a more accurate modeling of overall failure consequences.

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APPENDIX A: CONDITION IDEX TABLES

Table A-1: River flow measurement (manual or electronic)

River Flow									
Function	Provide measurement of flow upstream from the spillway.								
Excellent	Providing data accurately and reliably including under extreme conditions and at required frequency. Adequate number (for flow monitoring) for dam safety purposes. Instrument regularly checked and calibrate								
Failed	Not providing accurate data, not functioning.								
	0 – 9	10 –	25 – 39	40 – 54	55 – 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Water Level Indicator and other measurement devices									
Providing data accurately, and reliably under extreme conditions and at required frequency. Adequate number (for flow monitoring) for dam safety Instrument regularly checked and	calibrated						X		
Inadequate frequency of measurement				X	X				
Poorly located or calibrated and/or inadequate number for dam safety purposes. Cannot be checked manually or	visually.	X	X						
Not functioning.	X								
Data acquisition device									
Recording data at required frequency, accurately and reliably.							X		
Low recording frequency but still adequate				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								
Data transmission									
Transmitting data at required frequency, accurately and reliably.							X		
Transmitting data at less than required frequency					X	X			
Unreliable with frequent breakdowns reported.		X	X	X					
Not accurate, not functioning	X								

Table A-2: Reservoir level indicator

Reservoir level indicator									
Function	Measure reservoir level								
Excellent	Providing accurate data, redundancy and no evidence of malfunction (water level in the reservoir) for dam safety purposes. Instrument regularly checked and calibrated.								
Failed	Not providing accurate data, not functioning.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Water level indicators									
Measuring level accurately and continuously and adequate number for dam safety purposes							X		
Inadequate water level indicators to determine the influence of wind on pool level				X	X	X			
Poorly located (influenced by gate opening or difficult to read)			X	X	X				
Inadequate frequency of measurement			X	X					
No redundancy (only one gauge near the dam or spillway) Cannot be checked visually or manually		X	X	X					
Not providing accurate data, not functioning	X								
Data acquisition device									
Recording data continuously accurately and reliably.							X		
Low recording frequency but still adequate				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								
Data transmission									
Transmitting data at required frequency, accurately and reliably.							X		
Transmitting data at less than required frequency				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								

Table A-3: Precipitation and temperature gauge network

Precipitation and Temperature Gauge Network (For a watershed, including data acquisition and storage)									
Function	Measure rainfall on watershed								
Excellent	Providing data accurately, continuously and reliably. Adequate number according to the size of the watershed for dam safety purposes. Instrument regularly checked and calibrated.								
Failed	Not providing accurate data, not functioning, no gauge in the entire watershed								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Precipitation and Temperature gauges									
Measuring rainfall accurately continuously and reliably. Adequate number according to the size of the watershed for dam safety purposes.							X		
Not accurate data or inadequate number of rain gauges			X	X	X				
Not providing accurate data, not functioning, no gauge in seNce in the entire watershed	X								
Data acquisition device									
Recording data continuously accurately and reliably.							X		
Low recording frequency but still adequate				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								
Data transmission									
Transmitting data at required frequency, accurately and reliably.							X		
Transmitting data at less than required frequency				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								

Table A-4: Snow measuring stations

Snow Measuring Stations									
Function	Measure snow cover on watershed								
Excellent	Measurement of snow cover depth at an adequate number of locations with sufficient frequency for dam safety purposes.								
Failed	Not measuring snow depth cover in the watershed where applicable.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Measurement of snow cover depth at an adequate number of locations with sufficient frequency for dam safety purposes							X		
Inadequate number of snow measurement locations and/or insufficient frequency of readings			X	X	X				
Not measuring snow depth cover in the watershed where applicable	X								

Table A-5: Weather forecasting

Weather Forecasting									
Function	Forecsat precipitation in the watershed								
Excellent	Weather forecasting system can predict major precipitation events for dam safety purposes.								
Failed	Unavailability of weather forecasting data.								
	0 --9	10 --24	25 --39	40 – 54	55 --69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Weather forecasting system can predict major precipitation. Accurate for dam safety purposes							X		
Unavailability of weather forecasting data	X								

Table A-6: Ice and debris

Ice and debris									
Function	Provide information to the operator on debris and ice conditions upstream from the spillway and manage ice and debris accumulation								
Excellent	Ice and debris monitoring in place.								
Failed	No ice and debris monitoring in place.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 —69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Ice and debris monitoring									
Ice and debris monitoring in place							X		
No ice and debris monitoring in place	X								
Ice and debris management									
Ice and debris management procedures are detailed, up-to-date, available to operators, used, and effectilm.							X		
Ice and debris management procedures are documented but haw not been used				X	X	X			
Outdated or difficult to implement **IDM**		X	X						
No **IDM**	X								
Ice and debris control equipment									
Ice and debris control is effective							X		
Ice and debris control in place but partially effective				X	X				
Ice and debris control not effecti%	X								

Table A-7: Third party data

Third Party Data									
Function	Obtain data from other rilier users.								
Excellent	Provide reliable data on schedule								
Failed	Unreliable data and/or with unacceptable delays. Data not prmided.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Provide reliable data on schedule							X		
Unreliable data and/or with unacceptable delays	X	X	X						
Data not provided	X								

Table A-8: Gate position indicator

Gate Position Indicator									
Function	Indicate the position of a spillway gate								
Excellent	Provides a true reading relative to the opened or closed position of the gate. Deice regularly checked and calibrated.								
Failed	Not providing accurate data, not functioning. Gate position indicator provides a false reading (relatiw to the opened or closed position of the gate).								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Gate position indicator									
Provides a true reading relative to the opened or closed position of the gate Device regularly checked and calibrated.							X		
Gate position indicator out of adjustment					X	X			
Not providing accurate data, not functioning Gate position indicator provides a false reading (relative to the opened or closed position of the gate)	X								
Data acquisition device									
Recording data continuously accurately and reliably.							X		
Recording data intermittently but still adequate				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								
Data transmission									
Transmitting data continuously accurately and reliably.							X		
Transmitting data at less than required frequency				X	X	X			
Unreliable with frequent breakdowns reported.		X	X						
Not accurate, not functioning	X								

Table A-9: Flow prediction model

Flow prediction model									
Function	Models the inflows and outflows of the watershed								
Excellent	Properly utilizes input data to generate accurate and timely flow predictions under normal and extreme events.								
Failed	Inaccurate non dependable or untimely predictions								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Properly utilizes input data to generate accurate and timely flow predictions under normal and extreme events						X	X		
Dependable under normal conditions, untested under extreme events			X	X	X				
Dependable under normal conditions, undependable or untimely under extreme events		X	X						
Inaccurate, undependable or untimely	X								

Table A-10 Decision process

Decision process									
Function	Clearly defined roles, responsibilities in determining the need to open a gate.								
Excellent	Clear and current decision process that promotes appropriate and timely decisions as events warrant. Process is documented and is tested on a regular basis.								
Failed	Not clearly defined process								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Clear and current decision process that promotes appropriate and timely decisions as events warrant. Process is documented and is tested on a regular basis.							X		
Clear and current decision process. Process is documented; however it has not been tested on a regular basis				X	X	X			
Decision process in place but is not documented.		X	X						
Roles and responsabilities not defined in decision process	X								

Table A-11: Telecommunication system

Telecommunication system									
Function	Provide communication between decision makers and local operators								
Excellent	Dedicated system designed to operate under extreme conditions, has been tested recently. Available at all times.								
Failed	No communication								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Dedicated system designed to operate under extreme conditions, has been tested recently. Available at all times							X		
Expected to be reliable under. extreme conditions, has not been tested recently. Available at all times					X	X			
Expected to be reliable under extreme conditions. System has not been tested recently.				X	X				
Vulnerable under extreme conditions.		X	X						
No Communication	X								

Table A-12: Public protection and warning system

Public Protection and WarningS_ystem									
Function	System to warn and protect the public against consequences of gate opening and spillway hazards (includes horns, strobe lights, warning signs, fencing, safety booms, video cameras, site checks, etc.).								
Excellent	Warning system including opening sequence protocol is effective and comprehensive.								
Failed	No public protection and warning system								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Warning system including opening sequence protocol is effective and comprehensive.							X		
System is effective but public response is doubtful				X	X	X			I
System is inadequate to warn and protect against spillway hazards and rapid water rise.		X	X						
No public protection and warning system	X								

Table A-13: Availability and mobilization (design flood)

Availability and Mobilization (Design flood)									
Function	Provide key personnel and resources required for operation of the spillway during the design flood.								
Excellent	Key personnel and resources can always be reached and can get to gate controls in a timely fashion.								
Failed	Key personnel or resources cannot reach gate in required time.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Availability									
Key personnel always available at the site or at the gate controls							X		
Key personnel available on call continuously						X			
On-call plan activated as needed					X	X			
Extensive up-to-date list of key personnel				X	X				
Short list of key personnel		X	X						
No or outdated list of available key personnel	X								
Mobilization (Time required to contact personnel, get the required equipement and reach the site)									
Mobilization not required (Personnel and resources always available at the site or at the gate remote controls)							X		
Mobilization can be achieved before reaching the critical pool level						X			
Mobilization can be achieved before reaching the maximum pool level (above the critical pool level)			X	X	X				
Mobilization cannot be achieved before reaching the maximum pool level	X	X							

Table A-14: Availability and mobilization (load rejection)

Availability and Mobilization (Load rejection)									
Function	Provide key personnel and resources required for operation of the spillway during the design flood.								
Excellent	Key personnel and resources can always be reached and can get to gate controls in a timely fashion.								
Failed	Key personnel or resources cannot reach gate in required time.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Availability									
Key personnel always available at the site or at the gate controls							X		
Key personnel available on call continuously						X			
On-call plan activated as needed					X	X			
Extensive up-to-date list of key personnel				X	X				
Short list of key personnel		X	X						
No or outdated list of available key personnel	X								
Mobilization									
Mobilization not required (Personnel and resources always available at the site or at the gate remote controls)							X		
Mobilization can be achieved before reaching the critical pool level						X			
Mobilization can be achieved before reaching the maximum pool level (above the critical pool level)		X	X						
Mobilization cannot be achieved before reaching the maximum pool level	X								

Table A-15: Operating procedures

Operatingprocedures										
Function	Provide detailed instructions for the proper operation of the gates.									
Excellent	Operating procedures are detailed, up-to-date and available to operators									
Failed	No operating procedures									
	0 –9	10 –24	25 –39	40 – 54	55 –69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Standard operating procedures (covers normal and emergency situations) (SOP)									
Standard operating procedures are detailed, up-to-date, available to operators and tested							X		
Standard operating procedures have not been fully tested.				X	X	X			
Outdated or difficult to implement standard operating procedures		X	X						
SOP do not cover emergency situations (fire, dam break, earthquake, flood exceeding spillway capacity)		X	X						
No standard operating procedures	X								
Autonomous operating procedures (covers normal and emergency situat						**ons) (AOP)**			
AOP are detailed, up-to-date and available to operators.							X		
AOP have not been tested				X	X	X			
Outdated or difficult to implement AOP		X	X						
AOP do not cover emergency situations (fire, dam break, earthquake, flood exceeding spillway capacity)		X	X						
No AOP	X								

Table A-16: Qualification and training of operator

Qualification and trainiq of operator										
Function	To insure that operators are qualified to operate the gates									
Excellent	Personnel are trained and practiced in the operation of the gates and are familiar with the site and standard operating procedures.									
Failed	Personnel are untrained, unpracticed and unfamiliar with the site and the standard operating procedures.									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments	
Indicator	**1**	2	3	4	5	6	7	S		
Personnel are trained and practiced in the operation of the gates and are familiar with the site and the standard operating procedures.							X			
Personnel are trained but unpracticed with the operation of the gates.					X	X				
Personnel are unfamiliar with standard operating procedures.				X	X					
Personnel are unfamiliar with the site			X	X						
Personnel are untrained and unpracticed with the operation of the gates.		X	X							
Personnel are untrained, unpracticed and unfamiliar with site and the standard operating procedures.	X									

Table A-17: Portable equipment for lifting gates

Portable equipment for lifting gates										
Function	Portable equipment that is required for operating the gates									
Excellent	Portable equipment is kept in good working order and is readily available									
Failed	Portable equipment can not be prolAded within the required time for operating the gate									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments	
Indicator	**1**	2	3	4	5	6	7	S		
Portable equipment is kept in good working order and is readily available							X			
Portable equipment is readily available but condition is unknown				X	X					
Portable equipment must be rented		X	X							
Portable equipment can not be provided within the required time for operating the gate	X									

Table A-1:8 Road

Road									
Function	To provide access to the site.								
Excellent	Travel by road is possible under adverse conditions without significant delay								
Failed	Road not available under atherse conditions or seasonally.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Travel by road is possible under atherse conditions without significant delays							X		
Travel by road is possible under atherse conditions but distance to site is a hindrance				X	X	X			
Roadways or bridges known to be vulnerable to slides, erosion, flooding, etc. but alternate road available			X	X	X				
Roadways or bridges known to be vulnerable to slides, erosion, flooding, etc. with no alternate road		X	X						
Road not available under atherse conditions or seasonally	X								

Table A-19: Alternate means of access

Alternate means of access									
Function	To provide access to the site in lieu of road access if required.								
Excellent	Alternate means of travel allowing access within required time under adverse conditions and recently tested								
Failed	Alternate means of access frequently not available								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Alternate means of travel allowing access within required time under adverse conditions and recently tested							X		
Helicopter or plane									
Company owned/leased helicopter or plane dedicated to operational staff and adequate landing area at site				X	X				
Helicopter or plane on call or shared and adequate landing area at site			X						
Landing site for helicopter or plane but no current use agreement		X							
No landing site	X								
Boat access									
Accessible by company boat on the waterway and dedicated to operational staff					X				
Accessible with boats available locally				X					
Accessible by company owned boat not near site			X						
No safe docking area available under flood conditions	X								
Ground access by specialized vehicles (ATV, snowmobile, etc.)									
Ground route accessible with specialized company vehicles and dedicated to operational staff				X	X				
Ground route accessible with specialized vehicles available locally			X	X					
Alternate means of access frequently not available.	X								

Table A-20: Local access

Local access									
Function	Provide access to gate controls								
Excellent	Access is possible during adverse conditions.								
Failed	Access impracticable during adverse conditions. Access is not structurally sound.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Pedestrian access									
Access is possible during adverse conditions							X		
Access is possible during adverse conditions but minor repairs are required. Excessive debris present.				X	X	X			
Access is possible during adverse conditions but is hazardous		X	X						
Access impracticable during adverse conditions.Access is not structurally sound	X								
Keys and locks									
Operators have the required keys to access all secured areas and equipment and locks are well maintained and identified							X		
Locks are not well maintained				X	X				
Operator does not have access to a full set of well-identified keys.	X								

Table A-21: Remote and on site controls

Remote and on site controls									
Function	Operate gate and equipment								
Excellent	Clearly labeled and properly maintained. Properly located and lighted.								
Failed	Improperly labeled controls. Improperly located or lighted.								
	0 — 9	10 — 24	25 — 39	40 --54	55 --69	70 —84	85 – 100	Score	Comments
Indicator	1	2	3	4	5	6	7	S	
Clearly labeled and properly maintained. Properly located and lighted.							X		
Correctly labeled but improperly located controls				X	X				
Controls or devices require excessive effort to be activated			X	X					
Gate or gate position indicatomot located in the line of sight of the operator (visual or remote camera)		X	X	X					
Improperly labeled controls. Improperly located or lighted	X								

Table A-22: Medium voltage overhead lines

Medium Voltage Overhead Lines									
Function	Supply power to the spillway.								
Excellent	Built to current codes and standards, and maintained to provide continuous service and assure that proper clearances are maintained.								
Failed	Loss of power.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Vegetation control									
Line is free of vegetation						X	X		
Some vegetation encroachment (<10 feet)			X	X	X				
Poor vegetation control (<3 feet)	X	X							
Lightning protection									
Protection according to codes and standards						X	X		
Inadequate lightning protection but not exposed			X	X	X				
Damaged or inadequate lightning protection and exposed	X	X							
Poles supports and accessories (insulators conductors)									
No visual damage						X	X		
Damaged poles, supports, and accessories	X	X	X						

Table A-23: Local or emergency generator

Local or Emergency Generator									
Function	Supply power directly to the spillway								
Excellent	Provides nominal power at the correct frequency and voltage. Able to assume required load within specified time parameters and provide continuous service.								
Failed	Will not start. Rejects load. Unable to obtain nominal frequency and/or voltage to lift the gate. Unable to heat gate if required								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Functional tests for alternator and engine (Tests performed periodically under load conditions and to be verified during inspections)									
Frequency and voltage									
Frequency and voltage within nominal values						X	X		
Frequency or voltage do not meet nominal values but can still operate the gates		X	X	X					
Frequency or voltage do not permit gate operation	X								
Eng. Temp. and oil pressure									
Engine temperature and oil pressure within nominal Ialues						X	X		
Engine temperature or oil pressure outside nominal values		X	X	X					
Extreme temperature (low or high) or no pressure	X								
Starting sequence									
Starting sequence successful at first trial						X	X		
Starting sequence successful within three trials			X	X					
Does not start within three trials	X								
Noise and vibration									
Engine runs without excessive vibrations or noise						X	X		
Engine runs with increasing vibrations or noise over time				X	X				
Functional test									
Functional test performed according to standards							X		
No periodic functional test		X							
Fuel									
Fuel according to specifications							X		
No fuel registry on site			X	X	X				
Contaminated or old fuel		X	X	X					
No fuel	X								
Batteries									
Sized and maintained for specified load						X	X		
Battery in service longer than its rated service life				X	X				
Improper electrolyte		X	X						
Battery discharged or faulty cells	X								

Battery charger									
Maintains battery charge at specified level						X	X		
Does not maintain battery charge at specified level	X	X							
Alternator									
Insulation resistance within specifications						X	X		
Decreasing trend in insulation resistance with time but still within specifications			X	X	X				
Insulation resistance outside specifications	X	X							
Lubrication system									
Oil is within specifications (quality and level)						X	X		
Contaminated or oil outside of specifications but at correct level			X	X	X				
Clogged filter			X	X					
Low oil level due to leaks or excessive consumption		X							
No oil or excessive viscosity	X								
Cooling system									
Fluid is within specifications (quality and level)						X	X		
Contaminated fluid or significant leak			X	X	X				
No fluid, or no fluid (or air) circulation	X								
Intake and exhaust system									
Unobstructed air intake and exhaust system with filter in place						X	X		
Inadequate filter or no filter				X	X				
Partly clogged air filter or reduced circulation or exhaust defect		X	X						
Blocked air intake or exhaust system	X								

Table A-24: Underground and encased cables (medium voltage)

Underground and Encased Cables (medium voltage'									
Function	Supply power to the spillway								
Excellent	Built to current codes and standards, and maintained to provide continuous service.								
Failed	Loss of power								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Insulation									
Performs the function and/or passes the standard testing procedures						X	X		
Does not perform the function nor passes the Standard Testing Procedures	X	X							
Terminations									
Adequate connection						X	X		
Loose connection		X	X	X					
Discoloration		X	X						
Cannot supply power	X								

Table A-25: Power feeder cables (low voltage)

Power feeder cables (low voltage'									
Function	Supply power to gate operating equipment								
Excellent	Built to current codes and standards, and maintained to provide continuous service.								
Failed	Loss of power.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Insulation									
Performs the function and/or passes the Standard Testing Procedures						X	X		
Does not perform the function nor passes the Standard Testing Procedures	X	X							
Terminations									
Adequate connection						X	X		
Loose connection		X	X	X					
Discoloration		X	X						
Cannot supply power	X								

Table A-26: Transformer

Transformer										
Function	Supply power at correct xoltage level									
Excellent	Built to current codes and standards, and maintained to provide continuous service at correct xoltage level.									
Failed	Cannot supply correct voltage level.									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments	
Indicator	**1**	2	3	4	5	6	7	**S**		
Dielectric (oil)										
Oil according to specifications							X			
Contaminated oil (presence of foreign matter, e.g.; moisture)		X	X	X	X					
Degraded oil (by arcing, aging, acidity)	X	X	X	X						
Dissolved gases	X	X	X	X						
Insulation										
Performs the function and/or passes the standard testing procedures (insulation resistance and power factor, etc.)						X	X			
Does not perform the function nor passes the standard testing procedures	X	X								
Windings										
Performs the function and/or passes the standard testing procedures (resistance and turns-ratio)						X	X			
Does not perform the function nor passes the standard testing procedures	X	X								
Cannot supply power	X									
Tank										
No leaks							X			
Inadequate oil lewl or oil leak	X	X	X	X	X					
SeNce life (based on utility standard practices)										

Table A-27: Power source transfer system

Power source transfer system									
Function	To transfer from normal source to altemate source and retum								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Functional test (transfer switch)									
Successful							X		
Failed	X								
Functional test (Manual transfer device)									
Successful							X		
Failed	X								

Table A-28: Ice prevention system (air bubbler)

Ice prevention system lair bubbler'									
Function	To keep gates ice free								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Functional test									
Upstream gate surfaces maintained ice free							X		
Upstream ice accumulation prevents operation of the gate	X								

Table A-29: Lighting system (normal and emergency)

Liohtina system (normal and emeraencv)									
Function	Provide appropriate illumination to assure safe spillway operation								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Functional test									
Safe level of lighting is provided							X		
Insufficient or impaired lighting (dirty, burned out or missing bulbs)		X	X	X	X				
Lighting system inoperable	X								

Table A-30: Limit switches

Limit switches									
Function	To permit operation only within specified range								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Functional test									
Operated successfully or passed simulated test							X		
Failed	X								

Table A-31: Ice prevention system (heating)

Ice prevention system jheating elements, fans, thermostats, gain heaters'									
Function	To keep gates and gains ice free and/or prevent corrosion								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Functional test									
Heat is maintained within specifications							X		
Some heating system components do not function but gate can still be operated in winter conditions		X							
Does not prevent ice accumulation or gate cannot be operated	X								

Table A-32: Distribution panel

Distribution panel									
Function	To provide power to lighting, heaters, fans, monitoring instrumentation, etc.								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Functional test									
Successful							X		
Failed	X								
Visual inspection									
No visible problems							X		
Loose connections			X	X					
Presence of moisture or corrosion		X	X	X					
Damaged seals		X	X	X					
Damaged or missing locks			X	X	X				
General condition		X	X	X	X	X			
Carbinet heating									
Operational							X		
Non operational		X	X	X					

Table A-33: Translation motor (electric)

Translation Motor (electric)									
Function	Transforms electric power into mechanical power								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Insulation									
Performs the function and/or passes the standard testing Procedures (insulation resistance)						X	X		
Does not perform the function nor passes the standard testing procedures	X	X							
Apparent Temperature									
Normal temperature range						X	X		
Overheating			X	X					
Overloading									
Current and voltage within name plate specifications						X	X		
Excessilm current at rated voltage		X	X	X					
Fault trip	X								
Impaired ventilation (open motor)									
Impaired ventilation (open motor)		X	X	X					
Bearings and bushings									
Adequate, and appropriate lubrication						X	X		
Inadequate lubrication		X	X	X					
No rotation due to seizing	X								
Noise and vibrations									
Motor runs without excessilm noise or vibrations						X	X		
Motor runs with increasing noise or vibrations over time				X	X				

Table A-34: Lifting motor (electric)

Lifting Motor (electric)										
Function	Transforms electric power into mechanical power									
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.									
Failed	Cannot provide expected service									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Insulation									
Performs the function and/or passes the standard testing procedures (insulation resistance)						X	X		
Does not perform the function nor passes the standard testing procedures	X	X							
Apparent Temperature									
Normal temperature range						X	X		
Overheating			X	X					
Overloading									
Current and voltage within name plate specifications						X	X		
Excessilm current at rated voltage		X	X	X					
Fault trip	X								
Impaired ventilation (open motor)									
Impaired ventilation (open motor)		X	X	X					
Bearings and bushings									
Adequate, appropriate lubrication						X	X		
Inadequate lubrication		X	X	X					
No rotation due to seizing	X								
Noise and vibrations									
Motor runs without excessilm noise or vibrations						X	X		
Motor runs with increasing noise or vibrations over time				X	X				

Table A-35: Motor control center or individual control panel

Motor Control Center or Individual Control Panel										
Function	Provide power to the motor									
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.									
Failed	Cannot provide expected service									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Functional test (transfer switch)									
Successful							X		
Failed	X								
Visual inspection									
Discolored or pitted contacts		X	X	X					
Loose connections			X	X					
Audible noise			X	X					
Presence of moisture or corrosion		X	X	X					
Damaged seals		X	X	X					
Damaged or missing locks			X	X	X				
Cabinet heating									
Operational							X		
Not operational		X	X	X					

Table A-36: Cam switches

Cam switches									
Function	To commutate the resistances in the rotor circuit of wound-rotor motor								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Functional test									
Controls the speed and torque of the motor and permits rewrse direction							X		
Does not control the motor as expected		X	X						
Fails to control the motor	X								
Overheating or arcing									
Improperly adjusted contacts (Misalignment and/or inadequate pressure)		X	X	X					
Dirty or burned contacts		X							

Table A-37: External resistors

External resistors									
Function	Add or remove resistance in the circuit of the rotor (wound-rotor motor)								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Functional test									
Permits full control of the speed and torque of the motor							X		
Fail to adequately control the motor (missing or faulty resistor)		X							
No response from the motor	X								

Table A-38: Inverter control system

Inverter control system {includes the rectifier system)									
Function	Permits variable frequency control of the translation or lifting motor								
Excellent	Built to applicable codes and standards, and maintained to provide the expected service.								
Failed	Cannot provide expected service.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Functional test									
Provide controlled variable speed and torque of the motor							X		
Fails to operate the motor	X								

Table A-39: Screw and nut (screw-type hoist)

Screw and Nut (Screw-type hoist)										
Function	Transfer shaft rotation into gate movement									
Excellent	No warping, no wear, geometry according to specifications, uncontaminated grease.									
Failed	Warped enough to jam the mechanism, broken, split, missing threads, enough surface damage/corrosion to cause excessive friction									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
No warping, no wear, geometry according to specifications, uncontaminated grease.							X		
Surface Contaminants on grease or slight warping on screw with some damage or wear to threads of nut					X	X			
Inappropriate lubrication			X	X	X				
Excessive friction/noise, vibration and jumping, presence of metal shavings		X	X						
Warped enough to jam the mechanism; broken, split, missing threads; enough surface damage/corrosion to cause excessive friction	X								

Table A-40: Bearings

Bearings (Radial, thrust, power screw assembly)									
Function	Provide low friction support to rotating parts								
Excellent	Well lubricated and without abnormal noise or vibration, no excessive play								
Failed	Does not provide support to the moving parts and accessories (wheels or gears). Does not allow free movement.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Normal noise or vibration, runs well							X		
Abnormal noise or vibration but still runs					X	X			
Abnormal noise or vibration with no lubrication or blockage of grease lines but still runs			X	X					
Abnormal noise or vibration with no lubrication or blockage of grease lines and cracked housing but still runs		X	X						
Seizing between pin/shaft and bushing. Rotation of pin in yoke/lug.	X	X							

Table A-41: Split bushing or journal bearing

Split Bushing or journal bearing									
Function	Provide low friction support to rotating parts								
Excellent	Well lubricated and runs without noise, no excessive play								
Failed	Moving parts seized or excessive friction.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Well lubricated and runs without noise, no excessive play							X		
Noise with lubrication with some wear				X	X	X			
Noise without lubrication, vibration or cracked housing, but still running		X	X						
Moving parts seized or excessive friction.	X								

Table A-42: Rotating shafts, supports, bearings and couplings

Rotatina Shafts, Support Bearinas and Couplinas									
Function	Transfer torque								
Excellent	No corrosion, minor surface rust, no dent, straight, no crack								
Failed	Broken or severely bent or misaligned so that it cannot rotate								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**S**	
Corrosion									
No corrosion							X		
Corrosion but no section loss						X			
Measurable section loss			X	X	X				
Severe pitting		X	X						
Warping or Misalignment									
No warping						X	X		
Slight warping or misalignment that does not affect the motor load				X	X				
Warping or misalignment that increases the motor load / lockout order		X	X						
Warping or misalignment that prevents movement	X								
Cracking									
No cracks							X		
Crack known to be non critical (after evaluation)				X	X				
New crack or growth in existing crack		X	X						
Split or broken shaft/couplings	X								
Missing bolts or components									
No missing bolts, distortion, or gap							X		
Missing bolts or distortion or gap	X	X	X						

Table A-43: Gear assembly (hoist)

	Gear assembly (exposed or encased) including associated bushina and bearina (hoist)								
Function	Provide speed reduction for hoist mechanism								
Excellent	Shafts and Gears well aligned, well lubricated (no contamination, correct type of lubricant, stable level), no parts missing, no surface defects, no pitting. No excessive noise, jump or vibration.								
Failed	Gear can not transmit torque or motion								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Noise, jump and vibration									
No excessive noise, jump, or vibration						X	X		
Any one of excessive noise, jump, or vibration		X	X	X	X				
Tooth wear, contact, and breakage									
No wear with full contact and properly meshed							X		
Minor wear					X	X			
Significant part of contact surface of teeth missing due to breakage or wear, or misalignment		X	X	X					
Teeth missing preventing rotation	X								
Anchor (fastener to shaft, key or pin) movement or deterioration									
Fastener in place and undamaged							X		
Key or pin is cracked		X	X						
Gear slipping on shaft	X								
Bearing or bushing wear									
Normal noise, runs smoothly						X	X		
Excessive noise or cracked housing, but still running		X	X						
Jammed	X								
Lubricant									
Well lubricated, no contamination, correct type of lubricant, correct level or complete coverage of grease							X		
Presence of contaminants, low level of oil, or change in oil condition or color (encased)				X	X	X			
Inadequate coverage of lubricant		X	X	X					
Presence of contaminants that could jam the gear (includes ice formation)		X	X						
Presence of contaminants that jams the gear	X								

Table A-44: Dedicated lifting connectors

Dedicated lifting connectors (Pins. lugs. devises, and chain connectors'									
Function	Connect gate to lifting mechanism								
Excellent	No cracks, no deformation, no corrosion, pin in place								
Failed	Cracked or cannot sustain load								
	0 – 9								Comments
Indicator	**1**								N/A
No cracks, no deformation, no corrosion									
Bent, distorted or severely corroded elements									
Cracked elements	X								
Missing parts	X								

Table A-45: Non-dedicated lifting connectors

Non-dedicated lifting connectors (Pins and dogging pins. lugs to the gate)									
Function	Connect gate to lifting mechanism								
Excellent	No cracks, no irregularity, no bending, pin well set with uniform bearing								
Failed	Broken or not in place or unable to insert								
	0 – 9								Comments
Indicator	**1**							s	
Undamaged and correctly aligned									
Misalignment, damaged,		X	X	X	X				
Misalignment, cracked, damaged, bent, or severely corroded and pin cannot be inserted or missing pin	X								

Table A-46: Clutch

Clutch									
Function	To engage or disengage shaft at will								
Excellent	No slipping while engaged and can be disengaged at will								
Failed	Impossible to transmit torque, cannot be engaged or disengaged.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	**s**	
No slipping while engaged and can be disengaged at will							X		
Minor slippage that still permits the power to be transmitted				X	X	X			
Major slippage that still permits the power to be transmitted but speed is reduced or merheating of plates		X	X						
Impossible to transmit torque, cannot be engaged or disengaged.	X								

Table A-47: Drum, sheaves and pulleys

Drum, sheaves and pulleys									
Function	To transfer load to wire ropes								
Excellent	No visible wear, no abnormal noise, freely rotating								
Failed	Broken flange that cannot retain wire rope. Seized pulley								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Visible or measurable wear									
No visible wear, no abnormal noise, freely rotating							X		
Localized indentations, scratches				X	X	X			
Damage or wear that may cause a slip or misalignment, or abnormal noise, or vibration of wire rope		X	X	X	X				
Broken flange that cannot retain wire rope, or seized pulley	X								
Corrosion									
Failure of paint system, spots of surface rust, no section loss						X	X		
Surface scale present, no significant or measurable section loss				X	X				
Significant or measurable section loss		X	X						
Holes, complete section loss	X								
Groove wear (sheaves and drums)									
No wear							X		
Uneven groove				X	X				
Metal missing at the bottom of the groove		X	X						
Wire rope clamps or anchors									
Proper contact and solidly fastened							X		
Loose connection or damaged clamp		X	X						
Missing clamp or anchor	X								

Table A-48: Hoist brake

Hoist Brake									
Function	To arrest motion of gate and hold gate in any position								
Excellent	Can arrest motion at any position, not seized								
Failed	Cannot arrest motion at any position, seizing of brake								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Can arrest motion at any position, not seized							X		
Limited slippage without impacting operation; no slip but vibration				X	X	X			
Limited slippage that impacts operation		X	X						
Continuous slippage, seizing of brake	X								

Table A-49: Carriage brake

Carriage Brake									
Function	To arrest motion of carriage at will								
Excellent	Can arrest motion at any position, not seized								
Failed	Cannot arrest motion at any position, seizing of brake								
	0 – 9								Comments
Indicator	**1**							s	
Can arrest motion at any position, not seized							X		
Limited slippage without impacting operation; no slip but vibration				X	X	X			
Limited slippage that impacts operation		X	X						
Continuous slippage, seizing of brake	X								

Table A-50: Fan brake

Fan Brake									
Function	To limit the speed of descent of a gate in absence of power supply								
Excellent	Clean, unobstructed airways, louvers well-aligned and secured, gate closes at the specified speed.								
Failed	Exceeds the specified closing speed of the gate								
	0 – 9								Comments
Indicator	**1**							s	
Clean, unobstructed airways, . louvers well-aligned and secured, gate closes at the specified speed							X		
Obstructed airways, unsecured louvers or damaged impeller		X	X	X	X	X			
Gate closes too fast	X								

Table A-51: Wire rope and connectors

Wire rope and connectors										
Function	Transmit lifting force to the gate									
Excellent	No broken wires, can bend easily on a sheave or drum, well lubricated, no corrosion									
Failed	Six or more broken wires, birdcaging, reduction in wire diameter > 10%									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Kinking									
No kinking							X		
Minor, kinking of a wire				X	X				
Major, kinking of one or more strand	X	X	X						
Corrosion									
No corrosion, well lubricated							X		
No surface grease			X	X					
Carbon steel wire rope or connectors below the water line, and not inspected, or corrosion		X	X						
Reduction in wire diameter>10%	X								
Outer wire wear, or breakage									
No outer wire wear, or breakage							X		
Nicks or surface gouges (round ropes)		X	X						
Nicks or surface gouges (flat ropes)		X	X						
Six or more broken wires within a lay	X								
Birdcaging	X								
Corrosion									
Even tension							X		
Uneven tension not preventing opening			X	X	X				
Uneven tension presenting opening	X								

Table A-52: Trunnion assembly

Trunnion Assembly									
Function	Allow rotation of the radial gate								
Excellent	Well lubricated and without abnormal noise or vibration, no excessive play or friction								
Failed	Does not rotate or excessive friction during gate operation								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Functional Test									
Runs well with head. Frequently and uniformly lubricated, free rotation between pin and journal and/or thrust bearing. Well-aligned pins.							X		
Normal noise or vibration, Runs well in dry conditions without head. Free rotation between pin and journal and/or thrust bearing. Well-aligned pins						X			
Abnormal noise or vibration or no lubrication or blockage of grease lines or cracked housing but still running		X	X	X					
Seizing between pin/shaft and bushing.Rotation of pin in yoke/lug.	X	X	X						
Pin lateral displacement in trunnion	X	X							
Lubrication									
Well lubricated							X		
No lubrication or lubrication condition unknown			X	X	X				
Corrosion									
External corrosion on the assembly						X			
Corrosion preventing the removal of the cover plate				X	X				

Table A-53: Trunnion beam and anchorage

Trunnion beam and anchorage									
Function	To provide structural support of trunnion assembly								
Excellent	No cracks, no discoloring, no corrosion, no displacement, no deformation, no loose or missing anchor bolts, no concrete spalling								
Failed	Loss of support								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
No cracks, no discoloring, no corrosion, no displacement, no deformation, no loose or missing anchor bolts, no concrete spalling							X		
Corrosion of the anchorage and bolts				X	X				
Excessive displacement of the anchorage (if data is available)			X	X	X				
Excessive deflection of anchor beam (if data is available)			X	X	X				
External post-tension rods corrosion			X	X	X				
Diagonal shear cracks in concrete trunnion beam		X	X	X					
Loss of support	X								

Table A-54: Chain and sprocket assembly

Chain and sprocket assembly										
Function	To transmit lifting force to gate									
Excellent	No wear/play, well aligned, no corrosion, free movement of the pins, well lubricated, no deformations of the links or sprocket, no missing retention clips, no missing chain guides									
Failed	Missing pin, link, or cracked link or severely damaged sprocket									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments	
Indicator	**1**	2	3	4	5	6	7	S		
No wear/play, well aligned, no corrosion, free movement of the pins, well lubricated, no deformations of the links or sprocket, no missing retention clips, no missing chain guides							X			
Corrosion visible on surface of chain				X	X	X				
Operates but not well lubricated				X	X	X				
Noise, jumping, or vibration		X	X	X	X					
Kinking, not impacting operation			X	X						
Links do not lay flat on the chain rack under self-weight				X						
Links must be forced to rotate over the sprocket		X	X							
Corrosion limiting rotation of links		X	X							
Kinking limiting operation	X	X								
Improper meshing of chain and sprocket	X	X								
Missing pin, link, or cracked link or severely damaged sprocket.	X									

Table A-55: Hydraulic cylinder assembly

Hydraulic cylinder assembly									
Function	To provide lifting force to gate								
Excellent	No leak in the hydraulic system. Operates properly along full stroke within specifications.								
Failed	No pressure buildup or no movement at release pressure								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
No leak in the hydraulic system. Operates properly along full stroke within specifications.							X		
Loss of pressure controllable by motor			X	X	X				
Corrosion/pitting of rod			X	X					
Oil leakage		X	X	X					
Insufficient pressure buildup or no movement at release pressure	X								

Table A-56: Fixed wheels for vertical lift gates

Fixed wheels for vertical lift aates										
Function	Reduce friction when operating gates									
Excellent	Roundness within tolerances, minimal rusting, freely rotating, no cracks, well aligned, correctly lubricated.									
Failed	Enough wheels do not rotate preventing lifting of gate. Enough friction to prevent lifting or closing									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Roundness within tolerances, minimal rusting and pitting, freely rotating, no cracks, well aligned, correctly lubricated.							X		
Vibrations, jerkiness, uneven motion not preventing lifting or closing of gate			X	X	X				
Seized or damaged wheel or bearing not preventing lifting or closing of gate		X	X	X					
Enough friction to prevent lifting or closing of the gate.	X								

Table A-57: Roller trains

Roller trains										
Function	Reduce friction when operating gates									
Excellent	Roundness within tolerances, minimal rusting, freely rotating, no cracks, well aligned. Casings undamaged and follow gate movement.									
Failed	Jammed rollers prevent lifting of gate. Broken cable. Debris block rollers. Casing severely damaged or missing rollers									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Roundness within tolerances, minimal rusting, freely rotating, no cracks, well aligned. Casings undamaged and follow gate movement.							X		
Vibrations, jerkiness.				X	X	X			
Uneven motion not preventing lifting or closing of gate			X	X	X				
Jammed or damaged roller not preventing lifting or closing of gate		X	X						
Jammed rollers prevent lifting of gate. Broken cable. Debris block rollers. Casing severely damaged or missing rollers.	X								

Table A-58: Carrying tracks

Carrying Tracks									
Function	Provides support for, and the means to displace the lifting structure to access all the gates of the spillway.								
Excellent	Alignment according to specsification, no missing parts or sections.								
Failed	Visible or measured misalignment, section missing that presents the carriage from moving or lifting.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Alignment, elevation, spacing (gauge)									
According to specifications							X		
Out of specification but no noticeable wear of track, crane can still lift gate and travel (without noise and sibration)					X	X			
Out of specification but no noticeable wear of track, crane can still lift gate and travel (with noise and sibration)				X					
Out of specification with noticeable wear of track can still lift gate and move freely			X						
Enough misalignment, so that crane may not/cannot lift gate or move freely	X	X							
Anchor									
Present							X		
1 - 2 consecutive missing, damaged or loose anchor			X	X	X				
More than 2 missing, damaged, or loose consecutive anchor	X	X	X						
Missing sections									
None							X		
At least one gate cannot be opened	X	X	X						

Table A-59: Lifting device structure

Liftin • Device Structure (concreteL										
Function	To provide support for hoisting deice (and carrying tracks for mobile hoisting device)									
Excellent	Comprehensixe structural inspection has been performed. All critical structural members fully accessible for inspection. No member deformations, no cracks, no exposed rebars, no concrete spalling or erosion. No loss of bearing support. No misalignment according to specifications.									
Failed	Inability to correctly position or operate the lifting deice or the lifting structure. Extensixe deterioration, visible member deformations. Loss of concrete section.									
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments	
Indicator	**1**	2	3	4	5	6	7	S		
Support for lifting structure or hoisting mechanism										
No misalignment in a dedicated hoisting mechanism							X			
Displacement and deterioration of the structure causing misalignment in a hoisting mechanism with no effect on lifting						X				
Displacement and deterioration of the structure causing misalignment in a hoisting mechanism with abnormal noise and vibration				X	X					
Displacement and deterioration of the structure causing misalignment in a hoisting mechanism with motor overload		X	X							
Displacement and deterioration of the structure causing misalignment in a hoisting mechanism that cannot be lifted	X									

Table A-60: Mobile structure to support a shared lifting device

Mobile structure to support a shared lifting device (including gantry crane)										
Function	Provide structural support for the hoisting device									
Excellent	Comprehensive structural inspection has been performed. All critical structural members fully accessible for inspection. No visible cracks, no visible member deformation, no corrosion, no missing bolts or members, no visible misalignment.									
Failed	Visible deformations, missing parts, or cracks of a load-carrying member. Corrosion resulting in the loss of more than 20% of the cross-section of critical structural member. Missing bolts or cracked welds on a fracture-critical member or connection (a non-redundant tensile member or connection whose loss would result in the collapse of the structure)									
	0 –9	10 — 24	25 –39	40 –54	55 –69	70 –84	85 — 100	Score	Comments	
Indicator	**1**	2	3	4	5	6	7	S		
Displacement and deterioration										
No misalignment in the hoisting mechanism							X			
Displacement and deterioration of the structure causing visible or measurable misalignment in a shared lifting device with no effect on lifting						X				
Displacement and deterioration of the structure causing visible or measurable misalignment in a shared lifting device with excessive noise and vibration				X	X					
Displacement and deterioration of the structure causing visible or measurable misalignment in a shared lifting device with motor overload		X	X							
Displacement and deterioration of the structure causing visible or measurable misalignment in a dedicated hoisting mechanism that cannot be lifted	X									
Anchor bolts										
Corrosion on nuts and bolts				X	X	X				
Cracks in the concrete around the bolt and or missing concrete around the bolt		X	X							
At least one missing bolt or nut	X									
Cracks										
No cracks							X			
Crack in compression member	X	X	X	X						
Crack in tension members, web plate, or tension or compression connections (missing or cracked weld, splices, bolts and rivet heads)	X	X								
Crack in a fracture critical member	X									
Distortion										
No distorsion							X			
Distorion in tension members										

Compression members and braces, web, and bolts	X	X	X						
Corrosion (Compression and tension members and flanges)									
Intact coating							x		
Loss of coating, surface scaling					x	x			
Visible loss of section (< 20%)			x	x					
Loss of section > 20%	x	x							
Missing or loose parts									
No missing of loose parts									
Missing bolts or rivet heads in a connection < 10%			X	X					
Missing bolt or rivet head in a stiffener or a brace of main	X	X	X	X					
Missing bolts or rivet heads in a connection > 10%	X	X							
Missing welds	x								

Table A-61: Approach and exit channel

Approach and exit channel **(Upstream and downstream apron including base of pier/ stilling basin/exit channel)**									
Function	Protect the downstream and upstream portion of the spillway channel from erosion associated with the flow of water during discharge. ProvAde unobstructed passage to the flow of water.								
Excellent	No cavitation damage or erosion. No sedimentation upstream. No obstructions downstream.								
Failed	Major erosion at foot of spillway at the foundation level compromising the stability of the dam. Obstructions to the flow of water from sedimentation or downstream blockage.								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Loss of concrete due to cracking, erosion, cavitation (Apron and stilling basin)									
No loss							X		
Depth < 4"					X	X			
4" to 6" or exposure of rebar				X					
> 6" up to 30% of as-built cross-section		X	X						
> 30% of as-built cross-section design load and no structural evaluation	X								
Loss of concrete due to cracking, erosion, cavitation (in pier and/or base)									
No loss							X		
Minor (<2")					X	X			
Exposure of rebar			X	X					
Undermine rebar	X	X							
Scour of foundation material (caused by full opening of gates), scours and potential scour of sidewalls and bottom of spillway channel									
No loss of foundation material							X		
Loss or potential loss of material without undermining of dam (including never used)				X	X	X			
Loss or potential loss of material with undermining of dam (including never used)	X	X	X						
Upstream sedimentation									
None							X		
Minor						X			
Important	X	X	X	X	X				
Downstream blockage									
None							X		
Minor						X			
Important	X	X	X	X	X				

Table A-62: Lifting device structure (steel)

Liftin • device structure (steel)									
Function	Provide structural support for the hoisting deice (and carrying tracks for mobile hoisting deice)								
Excellent	Comprehensilm structural inspection has been performed. All critical structural members fully accessible for inspection. No visible cracks, no visible member deformation, no corrosion, no missing bolts or members, no x.isible misalignment.								
Failed	Visible deformations, missing parts, or cracks of a load-carrying member. Corrosion resulting in the loss of more than 20% of the cross-section of critical structural member. Missing bolts or cracked welds on a facture critical member or connection (a non-redundant tensile member or connection whose loss would result in the collapse of the structure).								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Displacement and deterioration									
No misalignment in a dedicated hoisting mechanism							X		
Displacement and deterioration of the structure causing lAsible or measurable misalignment in a hoisting mechanism with no effect on lifting						X			
Displacement and deterioration of the structure causing lAsible or measurable misalignment in a hoisting mechanism with excessive noise and vibration				X	X				
Displacement and deterioration of the structure causing lAsible or measurable misalignment in a hoisting mechanism with motor overload		X	X						
Displacement and deterioration of the structure causing lAsible or measurable misalignment in a hoisting mechanism that cannot be lifted	X								
Anchor bolts									
No corrosion							X		
Corrosion on nuts and bolts				X	X	X			
Cracks in the concrete around the bolt and or missing concrete around the bolt		X	X						
At least one missing bolt or nut	X								
Cracks									
No cracks							X		
Crack in compression member	X	X	X	X					
Crack in tension members, web plate, or tension or compression connections (missing or cracked weld, splices, bolts and rivet heads)	X	X							
Crack in a fracture critical member	X								
Distortion									
No distortion							X		
Distortion in tension members and braces				X	X				

Distortion in compression members and braces, web, and bolts	X	X	X						
Corrosion (Compression and tension members and flanges)									
Intact coating							X		
Loss of coating, surface scaling					X	X			
Visible loss of section (< 20%)			X	X					
Loss of section > 20%	X	X							
Missing or loose parts									
No missing or loose parts							X		
Missing bolts or rivet heads in a connection < 10%			X	X					
Stiffener of brace of main member	X	X	X	X					
Missing bolts or rivet heads in a connection > 10%	X	X							
Missing welds	X								

Table A-63: Embedded parts

Embedded Parts (including sill)									
Function	To provide external support and bearing surfaces to the gate and seals. i. Embedded sill plate ii. Roller path and sealing surfaces iii. Lateral guides Note: Add a list of possible actions for further investigations.								
Excellent	Gate has been dewatered for inspection or obsenetions in accordance with specified schedule. - No misalignment, warping or distortion - Working heating elements - No lAsible surface defects (pitting, cracking, wearing, punctures, dents, missing sections) - Full structural support - No surface contaminants (crustaceans) - Gate has been tested under load and lifts with appropriate load and velocity								
Failed	- Warping that could bind the gate in place - Heating elements not working - Loss of structural support under the roller pads - Enough displacement of the structural support that could bind the gate in place - Enough displacement of the structural support under seismic loading that could damage the gate - Localized pitting or puncturing under the roller path (1/8" or greater) - Puncturing of the embedded part outside of the roller path								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	1	2	3	4	5	6	7	S	
Gate lifting effort Gate lifts under load without overloading hoist at rated speed							X		
Gate lifts under load with hoist overload		X	X	X					
Gate does not lift	X								
Geometrical alignment of roller path									
With measurement meeting specifications							X		
No Visual warping or no known displacement of supports in the absence of measurements				X	X	X			
Measurements that do not meet specifications	X	X	X	X	X				
Visual warping or known displacement of supports in absence of measurements	X	X	X						
Corrosion (confined to roller track path)									
Light surface scaling					X	X			
Pitting < 1/8" deep			X	X					
Pitting > 1/8" deep	X	X							
Roller track wear									
No wear							X		
< 10% of thickness				X	X	X			
> 10% of thickness	X	X	X						
Corrosion (Rest of embedded part - excluding roller track)									
Failure of paint system, spots of surface rust, no section loss						X	X		
<30% loss of cross-section [locally]					X	X			
> 30% loss of cross-section [locally]		X	X	X					
Puncture or holes	X	X							

Table A-64: Gate structure

Gate Structure									
Function	Supporting structure To hold the skinplate Skin plate in place and transfer water load to wheels or trunnion. Provide lateral support to girders, retain water, water tightness								
Excellent	Gate has been dewatered for inspection or obsemtions in accordance with specified schedule. Gate has been tested under design load and lifts and closes according to specifications. - No x.isual warping or member deformation - No loss of paint - No IAsible surface defects on members or - connections (pitting, cracking, wearing, puncture, missing sections) - No fractured or missing welds - No missing bolts or members								
Failed	Warping or member deformation that could bind or overload the gate. Corrosion resulting in the loss of more than 20% of the cross-section. Missing bolts or cracked welds on a facture critical member or connection (a non-redundant tensile member or connection whose loss would result in the collapse of the structure).								
	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Loading history									
Operated under design load and positilm structural evaluation							X		
Operated under design load but no structural evaluation			X	X	X	X			
Operated under design load but negative structural evaluation	X	X	X						
Never been operated under design load but positilm structural elaluation					X	X			
Never been operated under design load and no structural evaluation		X	X	X					
Never been operated under design load and negative structural elaluation	X	X							
Cracks									
No Cracks							X		
Cracks in skin plate if due to impact (tear)				X	X				
Cracks in compression member fatigue crack in skin plate	X	X	X	X					
Cracks in tension members, web plate, or tension or compression connections (missing or cracked weld, splices, bolts and rivet heads)	X	X							
Crack in a fracture critical member	X								
Distortion									
No Distortion							X		
Distortion in tension members and braces, skin plate				X	X				
Distortion in compression members and braces, web, bolts, and pins	X	X	X						
Corrosion (skin plate)									

Failure of coating and/or surface scaling present						X	X		
Visible loss of section (< 30%)			X	X					
Holes, > 30% section loss	X	X							
Corrosion (Compression and tension members and flanges)									
Intact coating							X		
Loss of coating, surface scaling					X	X			
Visible loss of section (< 20%)			X	X					
Loss of section > 20%	X	X							
Missing or loose parts									
No missing or loose parts							X		
Missing bolts or rivet heads in a connection < 10%			X	X					
Missing or lose part in a plate stiffener (bracing behind skin plate, skin plate stiffeners)			X	X					
Stiffener or brace of main member	X	X	X	X					
Missing bolts or rivet heads in a connection > 10%	X	X							
Missing welds	X								

Table A-65: Stoplogs, bulkheads (steel)

Stoplogs. bulkheads (steel)	
Function	Provide closure for dewatering inspection, maintenance, and rehabilitation of gates and possible emergency closure. Used as a gate.
Excellent	Comprehensive structural inspection has been performed. All critical structural members fully accessible for inspection. No visible cracks, no visible member deformation, no corrosion, no missing bolts or members, no lAsible misalignment.No loss of paint. Adequate sealing for safe working conditions downstream
Failed	Visible deformations, missing part, or crack of a load-carrying member. Warping/member deformation that could bind the bulkhead in place. Corrosion resulting in the loss of more than 20% of the cross-section. Missing bolts or cracked weld on a fracture critical member or connection (a non-redundant tensile member or connection whose loss would result in the collapse of the structure). Cannot be lowered or raised into position. Does not provide sufficient water tightness.

	0 – 9	10 – 24	25 – 39	40 – 54	55 — 69	70 – 84	85 – 100	Score	Comments
Indicator	**1**	2	3	4	5	6	7	S	
Previously installed successfully and a positive structural evaluation							X		
Previously installed successfully and no structural evaluation			X	X	X	X			
Cracks									
No cracks							X		
Crack in skin plate if due to impact (tear)				X	X				
Crack in compression member o fatigue crack in skin plate	X	X	X	X					
Crack in tension members, web plate, or tension or compression connections (missing or cracked weld, splices, bolts and rivet heads)	X	X							
Crack in a fracture critical member	X								
Distortion									
No distortion							X		
Distortion in tension members and braces, skin plate				X	X	X			
Distortion in compression members and braces, web, bolts, and pins	X	X	X						
Corrosion (skin plate)									
No corrosion							X		
Failure of coating and/or surface scaling present					X	X			
Visible loss of section (< 30%)			X	X					
Holes, > 30% section loss	X	X							
Corrosion (Compression and tension members and flanges)									
Intact coating							X		
Loss of coating, surface scaling					X	X			
Visible loss of section (< 20%)			X	X					
Loss of section > 20%	X	X							
Missing or loose parts									
No missing or loose parts							X		
Missing bolts or rivet heads in a connection < 10%			X	X					
Plate stiffener (bracing behind skin plate, skin plate stiffeners)			X	X					
Stiffener or brace of main member	X	X	X	X					
Missing bolts or rivet heads in a connection > 10%	X	X							
Missing welds	X								

APPENDIX B: CONDITION INDEX VALUES OF SPILLWAY GATE COMPONENTS

Probability of accurately classifying the component			**0.975**
Failure	**Mean**	**Standard deviation**	
	25	**12.5**	

Indicators	**Condition State**		
	Observed	**Max**	**Min**
Gathering Information		**0**	**0**
River Flow Measurement		0	0
Water level indicator	7	100	85
Data acquisition device	7	100	85
Data Transmission	6	84	70
Reservoir level indicator		0	0
Water level indicator	7	100	85
Data acquisition device	6	84	70
Data Transmission	7	100	85
Precipitation and temperature gauge		0	0
Precipitation and temperature gauges	6	84	70
Data acquisition device	7	100	85
Data Transmission	7	100	85
Snow measuring model	6	84	70
Flow prediction model	6	84	70
Weather forecasting	6	84	70
Ice and debris management	7	100	85
Monitoring	7	100	85
Management	7	100	85
Control Equipment	7	100	85
Gate position indicator		0	0
Position indicator	7	100	85
Data acquisition device	7	100	85
Data Transmission	7	100	85
Third party flow data	7	100	85
Decision Process		**0**	**0**
Data processing	7	100	85
Analysis	6	84	70
Decision process	6	84	70
Public Protection and Warning System	6	84	70
Operation procedure	6	84	70
Standard operating procedure	6	84	70

Autonomous operating procedures	6	84	70
Access and Operations	**7**	**100**	**85**
Availability and mobilization (load rejection)		0	0
Availability	7	100	85
Mobilization	7	100	85
Availability and mobilization (design flood)		0	0
Availability	7	100	85
Mobilization	7	100	85
Qualification/training of operators	7	100	85
Load access		0	0
Pedestrian access	7	100	85
Keys and locks	7	100	85
Lighting system	7	100	85
Power Supply		**0**	**0**
Local or emergency generators		0	0
Frequency and voltage	7	100	85
Engine temperature/oil pressure	7	100	85
Starting sequence	7	100	85
Noise and vibrations	7	100	85
Functional test	7	100	85
Fuel	7	100	85
Batteries	7	100	85
Battery charger	7	100	85
Alternator	7	100	85
Lubrication	7	100	85
Cooling system	7	100	85
Intake and exhaust system	7	100	85
Cables and Controls		**0**	**0**
Underground and encased cables		0	0
Insulation	7	100	85
Terminators	7	100	85
Power feeder cables		0	0
Insulation	7	100	85
Terminators	7	100	85
Transformer		0	0
Dielectric	N/A		
Insulation	7	100	85
Windings	7	100	85
Tank	N/A		
Power source transfer system		0	0
Test (transfer switch)	N/A		
Test (manual transfer device)	7	100	85
Supporting Structure		**0**	**0**

Lifting device structure (steel)		0	0
Displacement/deterioration	7	100	85
Anchor bolts	7	100	85
Cracks	7	100	85
Distortion	7	100	85
Corrosion	7	100	85
Missing or loose parts	7	100	85
Lifting device structure (Concrete)		0	0
Displacement/deterioration	7	100	85
Anchor bolts	7	100	85
Cracks	7	100	85
Distortion	7	100	85
Corrosion	7	100	85
Missing or loose parts	7	100	85
Gate #1			
Gate Structure and Support		**0**	**0**
Approach and exit channel		0	0
Loss of concrete apron	7	100	85
Loss of concrete pier/base	7	100	85
Scour of foundation	7	100	85
Upstream sedimentation	7	100	85
Downstream blockage	7	100	85
Embedded parts		0	0
Gate lifting effort	7	100	85
Geometrical alignment roller	5	69	55
Roller path corrosion	5	69	55
Roller tooth wear	7	100	85
Corrosion remainder	7	100	85
Gate structure		0	0
Loading history	7	100	85
Cracks	7	100	85
Distortion	7	100	85
Skin plate corrosion	7	100	85
Tension/compression corrosion	7	100	85
Missing or loose parts	7	100	85
Closure structure (stoplog, bulkheads)		0	0
Structural evaluation	7	100	85
Cracks	7	100	85
Distortion	7	100	85
Skin plate corrosion	7	100	85
Tension/compression corrosion	7	100	85

Missing or loose parts	7	100	85
Bottom and side seals	7	100	85
Ice prevention	7	100	85
Access and Control		**0**	**0**
Remote and onsite controls	7	100	85
Hoist #1			
Power Supply and Controls		**0**	**0**
Limit switch	7	100	85
Motor control center		0	0
Functional test	7	100	85
Visual inspection	7	100	85
Cabinet heating	N/A		
Cam switches		0	0
Functional test	7	100	85
Overheating or arcing	N/A		
Force Transmission		**0**	**0**
Split bushing/journal bearing	7	100	85
Rotating shaft		0	0
Corrosion	7	100	85
Warping or misalignment	7	100	85
Cracking	7	100	85
Missing bolts or components	7	100	85
Gear assembly		0	0
Noise, vibration and jump	7	100	85
Toothwear and contact	7	100	85
Anchor	7	100	85
Bearing/bushing wear	7	100	85
Lubricant	7	100	85
Wheel, axle and bearings	7	100	85
Lifting connectors (non-dedicated)	7	100	85
Lifting connectors (dedicated)	7	100	85
Drum sheaves and pulleys		0	0
Variable and measurable wear	7	100	85
Corrosion	7	100	85
Groove wear	7	100	85
Wire rope clamps/anchors	7	100	85
Brake (hoist)	7	100	85
Fan brake	7	100	85
Wire rope and connectors		0	0
Kinking	7	100	85
Corrosion	7	100	85
Outer wire wear/breakage	7	100	85
Tension	7	100	85

Lifting motor (electric)		0	0
Insulators	7	100	85
Apparent temperature	7	100	85
Overloading	7	100	85
Impaired ventilation	7	100	85
Bearings and bushings	7	100	85
Noise and vibrations	7	100	85

APPENDIX C: FAILURE RATES OF SPILLWAY GATE COMPONENTS

Mechanical Components:

	Actual Age of Component (years) (t)	Condition rating (1-5 Scale)	Environmental Factor (See Note 1)	Stress & Temperature Factor (See Note 2)	Condition Factor (See Note 3)	Characteristic Life (Years)	Corrected Characteristic Life (hours) =α'=α/K1*K2*K3	Weibull Shape Factor (From ETL 1110-2-560)	(Probability of Failure) Formula: F(t)= 1-exp (-t/α')^β)
Lock Components	50	C	K1	K2	K3	(α) (yrs)	(α') (yrs)	(β)	
Hydraulic Control Valves									
Ball Valve	50	5	1	1	1.0	50	50.00	2	0.632
Check Valve	50	4	1	1	1.1	45	40.91	1.5	0.741
Manual	50	3	1	1	1.2	60	50.00	1.5	0.632
Proportional/Throttle Valve (Solenoid)	50	2	1	1	1.3	40	30.77	1.5	0.874
Pressure Relief Valve	50	1	1.1	1.1	1.4	40	23.61	1.5	0.954
Hydraulic Cylinders									
Hydraulic Cylinder	50	5	1	1	1.0	60	60.00	1.5	0.533
Piston Rod (Ceramic Coated)	50	5	1	1	1.0	10	10.00	1.5	1.000
Piston Rod (Chromed)	50	5	1	1	1.0	60	60.00	3	0.439
Piston Rod (Stainless)	50	5	1	1	1.0	60	60.00	3	0.439
Hydraulic Piping									
Flexible Hose & Connections	50	5	1	1	1.0	20	20.00	1	0.918
Pipe (Carbon Steel)	50	5	1	1	1.0	40	40.00	2	0.790
Pipe (Stainless Steel)	50	5	1	1	1.0	75	75.00	2	0.359
Hydraulic Pumps and Motors									
Hydraulic Pump (Fixed)	50	5	1	1	1.0	50	50.00	3	0.632
Hydraulic Pump (Variable)	50	5	1	1	1.0	30	30.00	3	0.990
Hydraulic Motor (Fixed)	50	5	1	1	1.0	50	50.00	3	0.632
Hydraulic Motor (Variable)	50	5	1	1	1.0	30	30.00	3	0.990

Bearings											
Bronze sleeve Bushing	50	5	1	1		1.0	40	40.00	3		0.858
Roller Bearing	50	5	1	1		1.0	40	40.00	3		0.858
Self-lubricated Bushing	50	5	1	1		1.0	25	25.00	3		1.000
Chains											
Roller Chain	50	5	1	1		1.0	40	40.00	2		0.790
Shackle & Pin	50	5	1	1		1.0	35	35.00	2		0.870
Sprocket	50	5	1	1		1.0	60	60.00	3		0.439
Clutch											
Slip	50	5	1	1		1.0	30	30.00	2		0.938
Couplings											
Flexible Coupling	50	5	1	1		1.0	35	35.00	1		0.760
Rigid Coupling	50	5	1	1		1.0	50	50.00	1		0.632
Gear Reducers											
Parallel Gears	50	5	1	1		1.0	40	40.00	3		0.858
Right Angle Gear	50	5	1	1		1.0	38	38.00	3		0.898
Worm Gear	50	5	1	1		1.0	25	25.00	3		1.000
Open Gearing											
Beveled Gears	50	5	1	1		1.0	40	40.00	3		0.858
Helical Gears	50	5	1	1		1.0	38	38.00	3		0.898
Rack Gear	50	5	1	1		1.0	60	60.00	3		0.439
Sector/Spur Gear	50	5	1	1		1.0	60	60.00	3		0.439
Shafts, Pins Rollers											
Gate Lifting Stems	50	5	1	1		1.0	80	80.00	1		0.465
Pins	50	5	1	1		1.0	35	35.00	3		0.946
Pintles/Bushings	50	5	1	1		1.0	30	30.00	3		0.990
Rack Support Roller	50	5	1	1		1.0	43	43.00	3		0.792
Rotating Shafts	50	5	1	1		1.0	80	80.00	1.1		0.449
Stem Nut	50	5	1	1		1.0	35	35.00	2		0.870
Trunnion Pin/Bushings	50	5	1	1		1.0	38	38.00	3		0.898
Vertical gate (Wheel Assembly Rollers)	50	5	1	1		1.0	40	40.00	3		0.858
Water Valves											
Butterfly Valve	50	5	1	1		1.0	50	50.00	1.5		0.632
Vertical Lift (Roller gate)	50	5	1	1		1.0	50	50.00	1.5		0.632
Wire Rope											
Wire rope drums	50	5	1	1		1.0	75	75.00	3		0.256
Wire Rope (Round Carbon Steel)	50	5	1	1		1.0	20	20.00	3		1.000
Wire Rope (Round Stainless Steel)	50	5	1	1		1.0	20	20.00	3		1.000
Wire rope Sheaves	50	5	1	1		1.0	33	33.00	3		0.969

Wire Rope (Single/Multiple Sheave's)	50	5	1	1		1.0	20	20.00	3		1.000
Wire Rope (Spiral Plate)	50	5	1	1		1.0	5	5.00	3		1.000
Wire Rope (Gate Connection)(Pins, Cable)	50	5	1	1		1.0	50	50.00	2		0.632
Miter Gates											
Sector arms	50	5	1	1		1.0	73	73.00	1		0.496
Strut arms - buffered	50	5	1	1		1.0	35	35.00	1		0.760
Strut arms - rigid	50	5	1	1		1.0	50	50.00	1		0.632
Gudgeon Pin/Bushings	50	5	1	1		1.0	43	43.00	3		0.792
Rack support beam	50	5	1	1		1.0	60	60.00	1		0.565
Culvert Valve											
Bell cranks	50	5	1	1		1.0	78	78.00	1		0.473
Crosshead/Guide	50	5	1	1		1.0	73	73.00	1		0.496
Strut	50	5	1	1		1.0	43	43.00	1		0.687
Strut Spindle Pin	50	5	1	1		1.0	25	25.00	3		1.000
Misc. Components											
Brake (Electromechanical)	50	5	1	1		1.0	45	45.00	3		0.746
Grease/Lube System	50	5	1	1		1.0	30	30.00	1.5		0.884
Bridge Crane Hoist Machinery	50	5	1	1		1.0	40	40.00	3		0.858
Screw Type Actuators	50	5	1	1		1.0	30	30.00	3		0.990
Tow Haulage Unit (Hydraulic)	50	5	1	1		1.0	30	30.00	3		0.990
Tow Haulage Unit (Mechanical)	50	5	1	1		1.0	48	48.00	3		0.677

Electric Components:

Lock Components	Actual Age of Component (years) (t) 50	Environmental Factor (See Note 1) K1	Stress & Temperature Factor (See Note 2) K2	Characteristic Life (Years) (α) (yrs)	Corrected Characteristic Life (hours) =α'=α/K1*K2 (α') (yrs)	Weibull Shape Factor (From ETL 1110-2-560) (β)	(Probability of Failure) Formula: F(t)= 1-exp (-t/α')^β)
Cables							
Buried/Submerged Cable	50	1	1	60	60.00	1	0.565
Portable/Flexible Cable	50	1	1	28	28.00	1	0.832
Duct/Cable Tray	50	1	1	80	80.00	1	0.465
Controls							
PLC systems	50	1	1	18	18.00	1	0.938
ElectroMechanical Drives							
DC Rectifier (brakes)	50	1	1	35	35.00	1	0.760
Electric Motors (new and rebuilt	50	1	1	68	68.00	1	0.521
Standby Generator	50	1	1	50	50.00	1	0.632
Motor Control							
Motor Control Centers (MCC)	50	1	1	83	83.00	1	0.453
Motor Starter (Full Voltage)	50	1	1	63	63.00	1	0.548
Motor Starter (Reduced/Variabl	50	1	1	50	50.00	1	0.632
Motor starter (VFD)	50	1	1	35	35.00	1	0.760
Power Distribution							
Bus Duct (Electonic)	50	1	1	95	95.00	1	0.409
Circuit Breakers	50	1	1	63	63.00	1	0.548
Power Panelboard	50	1	1	78	78.00	1	0.473
Power Recepticle	50	1	1	50	50.00	1	0.632
Power Utility	50	1	1	4	4.00	1	1.000
Service Transformer	50	1	1	55	55.00	1	0.597
Switchboards	50	1	1	83	83.00	1	0.453
Switchgear	50	1	1	78	78.00	1	0.473
Transfer Swich (Automatic)	50	1	1	30	30.00	1	0.811
Transfer Switch (Manual)	50	1	1	65	65.00	1	0.537
Sensors							
Selysn Motor	50	1	1	43	43.00	1	0.687
Switches							
Travellng nut limit switch	50	1	1	65	65.00	1	0.537