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# RELIABILITY ANALYSIS APPROACH FOR OPERATIONS PLANNING OF HYDROPOWER SYSTEMS

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Many existing hydropower storage facilities were built decades ago and components of these aging infrastructure facilities have higher risk of failure. Insufficient capacity or forced outages of the spillway and other waterway passage facilities during flooding incident could potentially increase the probability of dam safety incidents leading to public safety concerns. Currently approaches used to assess the risk and uncertainty in operational decision making are mainly based on qualitative assessment and expert judgment and can be significantly improved by the development of a framework that formally incorporates both qualitative and quantitative reliability analysis methods. Event tree analysis and fault tree analysis have traditionally been used in dam safety risk analysis, with results subject to data adequacy and availability. Our research shows that other methods, such as nonparametric analysis and Monte Carlo simulation techniques can yield good results as well. This study investigated the application of reliability analysis methods to existing hydropower storage facilities, with the objective of developing a new systems engineering based approach for risk and uncertainty analysis to assess and manage the risks of hydropower system operations. Our approach integrates reliability-based methods with hydro system optimization modeling to develop an operational reliability-based modeling framework and to formally treat risk and uncertainty in operations planning. This approach incorporates different sources of uncertainty that are typically encountered in operations planning of these systems, including failure probability of hydro system components such as non-power release structures and turbine facilities. This paper presents the framework we have developed and illustrates the application of our investigation for a hydropower system facility in British Columbia, Canada.

## INTRODUCTION

BC Hydro owns, operates and maintains 40 dam facilities throughout British Columbia as a major part of its generating system. Most of BC Hydro hydropower facilities are in the middle service life, but some are at the wear-out phase and BC Hydro is in the process of rehabilitating a number of these facilities such as the John Hart generating facility. There has been a spillway gate rehabilitation and replacement program since 2005 to address reliability issues across BC Hydro's fleet of facilities with spillway gates. The upgrades include spillway gate hoists and towers, and all systems such as the electrical, mechanical, civil, and control systems. Spillway gates act as movable barriers impounding the water in the reservoir as well as controlling the amount of water that can be discharged from the reservoir. These gates are critical components of any storage dam and are generally used in times of flood when high inflows exceed the ability of generation units to pass the flood water.

Reliability analysis methods have gained recognition both in academic field and engineering practice in recent years. Event tree analysis is a logical model that includes all possible chains of failure events resulting from an initiating event. Stedinger *et al* [1] applied the concept of event tree analysis to describe the random factors contributing to major inflow floods, reservoir operation, and possible downstream damages. They presented evaluation of the failure probability using sampling methods. A fault tree analysis is a top-down deductive graphical technique used to analyze complex spillway systems. Fault trees for each top event for spillway gates as well as for the associated operating equipment were developed by Lafitte [2]. Weibull distribution is one of the best-known distribution models in reliability analysis. It adequately describes observed failure of many different types of components and phenomena. A spillway gate has multiple components and failure modes. In this paper, reliability of individual mechanical and electrical components is assessed as well as the interrelationship between components. The spillway gate is analyzed as a system and relative contribution of each component to system failure over time is revealed. Other alternative analysis methods can be based on historical performance data of spillway gate operation; the nonparametric analysis and Kaplan-Meier estimator [3] are applied in the reliability analysis. Nonparametric analysis provides powerful results because the reliability calculation is not constrained to fit any particular predefined lifetime distribution and Kaplan-Meier estimator provides an elegant solution to estimate reliability when censored data are encountered [4].

Risk is defined as the combination of the probability and consequences of failure. Failure occurs when hydropower facility no longer operates as intended. The operation of a large and complex hydroelectric system including non-power release facilities requires careful management and continuous planning. Operation planning is guided by safety of lives and property, load obligations and maximizing the value of generating resources. The operation process involves a wide range of input information such as inflow, generation unit availability, market price and so on. In addition, system constraints, individual component constraints, dam safety, environmental and other physical data are taken into account. Computer models are employed to simulate the operation of the hydroelectric system to maximize the financial value of system output while meeting system and plant constraints. A multi-objective simulation optimization model Operations Planning Tool (OPT) has been developed to manage generation and water resources meeting environmental constraints and economic goals. Reliability analysis of spillway gates could be integrated with hydro system optimization modeling to develop an operational reliability-based modeling framework and to formally treat risk and uncertainty in operations planning.

## RELIABILITY ANALYSIS

The continuous probability approach to reliability is represented by the reliability function which is the probability that an item has survived to time *t*. The mathematical expression can be summarized by:

$$R(t) = P(T > t) \tag{1}$$

where $T$ is the time of failure and $t$ is the designated period time for the operation of the item.

The Weibull distribution is one of the most commonly used distribution in reliability analysis. Its wide application is due to the flexibilities to model different kinds of failure behaviors. The cumulative density function (CDF) of the Weibull distribution is as follows:

$$F(t) = P(T \le t) = 1 - \exp[-(\frac{t-\tau}{\alpha})^{\beta}], \alpha > 0, \beta > 0, t \ge \tau \ge 0 \tag{2}$$

where $\alpha$ is a scale parameter, $\beta$ is the shape parameter which determines the shape of the distribution and $\tau$ is the location parameter that indicates the difference in time between the original installation and replacement. The reliability function (for $\tau$=0) is:

$$R(t) = 1 - F(t) = \exp[-(\frac{t}{\alpha})^{\beta}], \alpha > 0, \beta > 0, t \ge 0 \tag{3}$$

**Mechanical and Electrical Components and System Reliability**

Mechanical and electrical components are typically complex and made up of many parts which have different modes of failure. These failure modes are associated with many ambiguous variables, e.g. operating environment. Usually failure data are not available. Spillway gate facilities for which data are not available require the analysis to be completed using data from larger systematic samples of similar equipment from the published failure rate data. If the component is in use most of the time, it is assumed that it is in use for a full calendar year rather than just the operational time.

The reliability of a mechanical or electrical system is computed by creating a series-parallel system of the individual components. If the failure of any single component will lead to the failure of entire structure, the system is considered to be a series system. For a series system with $n$ independent components, the system reliability over time $t$ is:

$$R_{system,series}(t) = \prod_{i=1}^{n} R_i(t) \tag{4}$$

If system failure occurs only after the failure of all components, the system is considered to be a parallel system. The reliability for the parallel system is given by:

$$R_{system,parallel}(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)] \tag{5}$$

Series system is reflective of the interrelations between components of a spillway gate since only a small portion of components are in parallel or on standby [5]. Weibull distribution is used to perform the reliability analysis for each component where the parameters $\alpha$ and $\beta$ were selected in published data from sources such as the Reliability Analysis Center [6]. Figure 1 illustrates the reliability of major mechanical and electrical components in a spillway radial gate over 10 years.

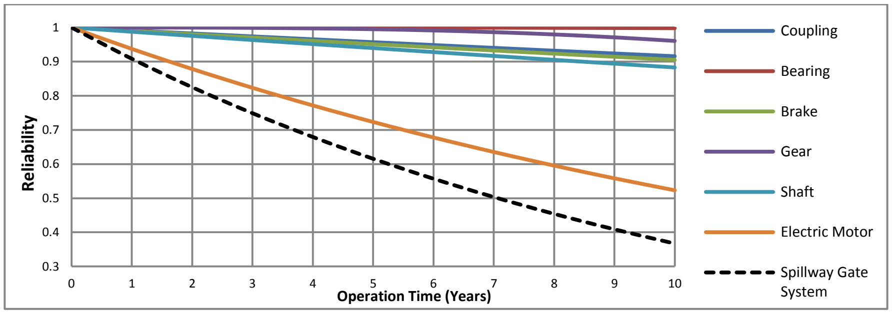


Figure 1. Reliability of major components in spillway radial gate system

**Nonparametric Analysis**

Life data of hydropower facilities can be classified into two types, complete and censored data. If equipment does not fail in observation time *t*, then *t* is considered to be a lower limit of the time to failure and can be used for estimation. In hydropower facilities such as turbines and spillway gates, this type of data is commonly encountered, and is called right censored data. In the following discussion, empirical reliability function from a complete data set (i.e. all the time to failure is observed) is described. Then the Kaplan-Meier estimator is introduced to handle censored data. Arrange the *n* historical time to failure data in an ascending order:

$$t_1 < t_2 < ... < t_{n-1} < t_n \tag{7}$$

An empirical estimated reliability function with complete data is developed as follows:

$$R_n(t) = \begin{cases} 1, (t < t_1) \\ \dfrac{n-i}{n}, (t_i \le t < t_{i+1}), (1 \le i < n) \\ 0, (t \ge t_n) \end{cases} \tag{8}$$

where if *m* failure events fail the same time $t_j$, a simple adjustment is required:

$$R_n(t) = \frac{n-m}{n}, (t_j \le t < t_{j+1}) \tag{9}$$

For censored data, the Kaplan-Meier estimation procedure is introduced based on a sample of *n* data, among which *k* values are distinct observed time to failure ($k<n$). The estimate of the reliability function is given by:

$$R_n(t) = \begin{cases} 1, (t < t_1) \\ \prod_{j=1}^{i} \dfrac{n_j - m_j}{n_j}, (t_i \le t < t_{i+1}), (1 \le i < k) \\ 0, (t \ge t_k) \end{cases} \tag{10}$$

where $n_j$ refers to the number of operating items right before $t_j$ and $m_j$ is the number of failures at time $t_j$.

One can transform the Weibull distribution to a linear function by taking natural logarithm of both sides twice of Eq. (3):

$$y = \beta x - \beta \ln \alpha \text{, where } \begin{cases} y = \ln[-\ln R(t)] \\ x = \ln t \end{cases} \tag{11}$$

With the result of computed reliability from the nonparametric analysis, a linear curve fitting can be done using Eq. (11). If the discrete points are aligned, the underlying distribution of nonparametric analysis is assumed to follows the Weibull distribution. An example of such analysis is demonstrated by analyzing historical forced outage data recorded in a turbine generating unit at one of the BC Hydro facilities in Figure 2. The scattered points align well with a straight line, and a regression analysis provides the following result:

$$y = 0.5119x - 2.2441 \text{ with } R^2 = 0.9692 \tag{12}$$

which shows that Weibull distribution is an appropriate distribution for the reliability analysis of this and similar hydropower facilities. The scale parameter and shape parameter can be estimated as well.

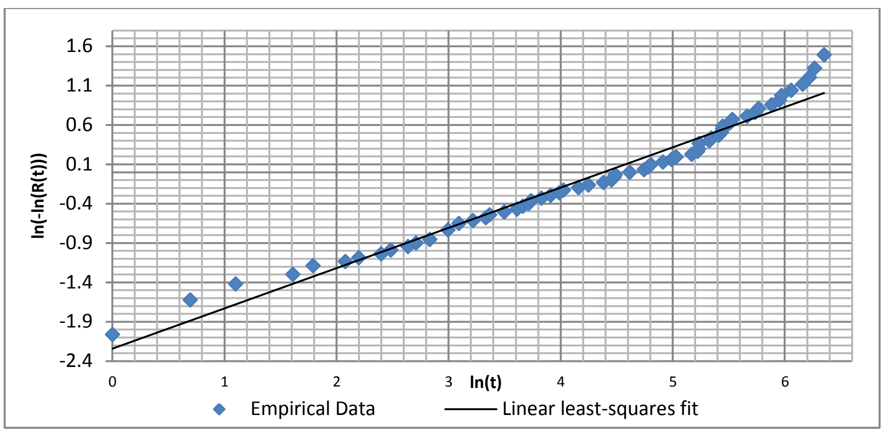


Figure 2. Weibull plot of the nonparametric analysis reliability of a turbine generating unit

## RELIABILITY-BASED HYDRO OPERATIONS PLANNING

### Operations Planning Tool

The Operations Planning Tool (OPT) is a simulation model to optimize the operation and planning of hydropower systems meeting economic, environmental and social constraints in British Columbia. It is formulated as a linear programming optimization problem using AMPL [7] and solved using CPLEX solver packages. A graphical user interface (GUI) is currently under re-development to provide a user-friendly environment for coupling the AMPL model with CPLEX solver and assisting user-specified input. Figure 3 shows the general OPT framework with input data and output variables including reservoir elevation, spill through different non-power release structures, daily turbine discharge, hydropower generation and energy revenue, etc.

Hydropower operations have constraints on the preferred ranges of reservoir elevations and spillway releases. Preferred range of reservoir elevation is specified through references from

BC Hydro operation studies to prevent overtopping or overdraft of the reservoir. Release through spillway gates is also preferred to be operated within certain range, for instance, to meet the target flow to protect salmon habitat. Deviations outside the range are not desirable and the preference zone is therefore established by introducing the penalty function. Figure 4 presents the piecewise linear penalty function used as a soft constraint to restrict optimal reservoir elevation to be in preferred operating ranges.

The objective function in the model is expressed as:

$$Minimize: \sum w_1 \times ElPen + \sum w_2 \times SpillPen - \sum w_3 \times G \times P \tag{13}$$

where *w* is the weight coefficient used to specify the relative importance of each term in the objective function based on different operation requirements, *ElPen* and *SpillPen* are the penalty values of reservoir elevation and spillway release respectively, *G* refers to hydropower generation and *P* is the market price.

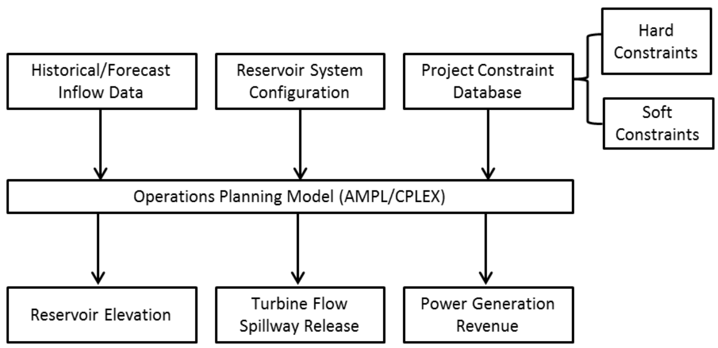


Figure 3. General OPT model framework

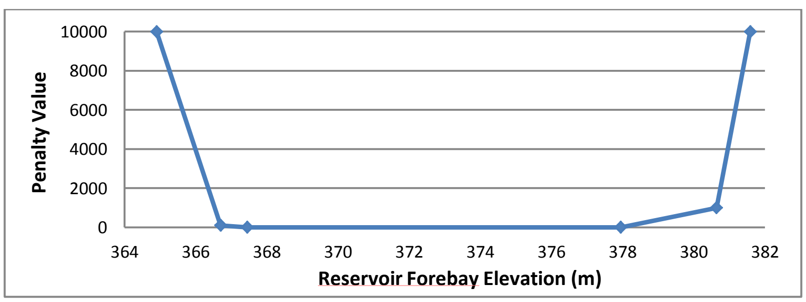


Figure 4. Penalty function of a typical reservoir

**Case Study – Cheakamus River**

The Cheakamus River originates in the Coast Mountains, running northwest toward the famous ski resort Whistler before turning south to meet the Squamish River in British Columbia, Canada. The Cheakamus Project comprises a storage reservoir forming the Daisy Lake, a power intake linked to Daisy Lake by a canal and a power plant located on the Squamish River. Normal operation levels for Daisy Lake Reservoir are between 366.97m and 377.95m and discharge facilities for Daisy Lake Reservoir include the powerhouse tunnel with two generating units, two radial spillway gates, overflow weir, a lower level sluice gate and a hollow cone valve for fish flow. Failure of spillway gates to operate on demand may result in overtopping of the dam, which could lead to loss of life, financial and social consequences, and damage to the environment. This is particularly serious at the Cheakamus system where the reservoir is small and rapid changes in water level could occur in such incidents. During the flood in October 2003 peak flow lasted for extended period and the rise in reservoir water level was 5 m in 24 hours. Reliability analysis spillway gate is necessary for operations planning.

Monte Carlo simulation is performed to simulate the spillway gate failures. A random number between 0 and 1 is generated to represent the probability of an event occurring at a given time, in this case spillway gate failure. With the reliability function of radial spillway operating gate in the Cheakamus Dam achieved by analyzing historical performance data and yielded the following reliability empirical model:

$$R(t) = \exp[-(\frac{t}{476})^{1.3334}], t \geq 0 \quad (14)$$

Monte Carlo method can simulate the time to failure. The repair time of the gate is also generated by such simulation which fits to the lognormal distribution.

A high inflow year scenario (1995) has been selected to demonstrate the study. Hydrology data from that year were collected. River and reservoir system configuration and hydropower facilities such as turbine generating units and spillway gates are defined in OPT. Assumption is made that the failure mode is failure to open the spillway gate completely when required (i.e. the spill release is zero). The reliability analysis and simulation gives a sample result of failure time and repair time of the two radial spillway operating gates (SPOG 1&2) shown in Table 1.

Table 1. Simulation result of spillway operating gates failure in Cheakamus Dam in 1995

| | Failure Start | Failure End |
|---|---|---|
| SPOG1 | July 17 | July 29 |
| SPOG2 | April 26 | May 22 |

Decision variables of operations planning from the OPT model result in the spillway gate failure cases and when they are fully functional are presented in Figure 5, 6 and 7. It can be seen that the SPOG1 failure did not cause significant rise in reservoir level while SPOG2 failure coincided with high inflow and relatively high reservoir level and resulted in significant rise in water level in the reservoir.

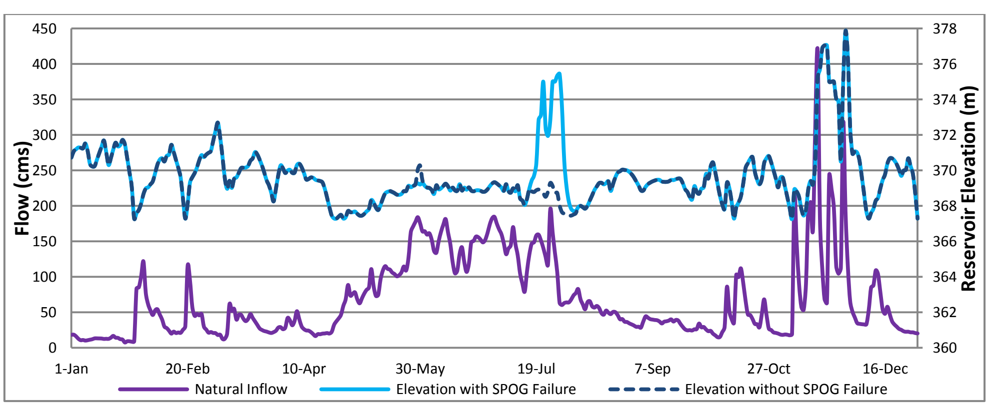


Figure 5. Daisy Lake reservoir elevation at Cheakamus River

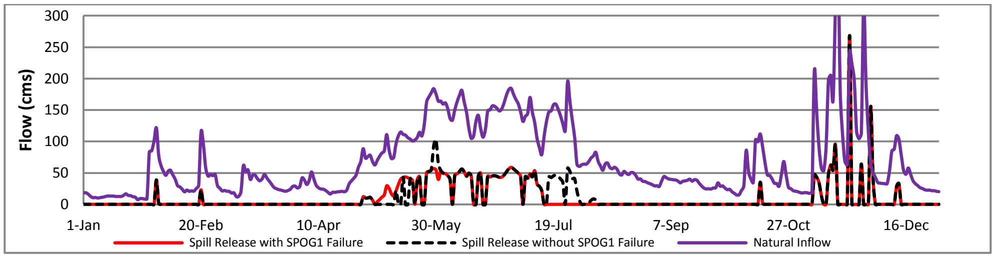


Figure 6. Cheakamus Dam SPOG1 spill release

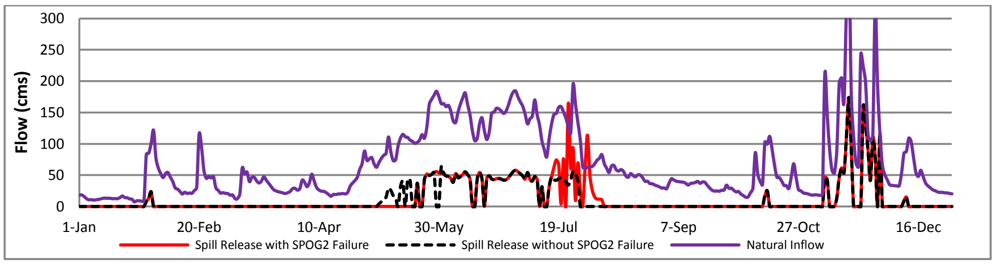


Figure 7. Cheakamus Dam SPOG2 spill release

## CONCLUSION

Reliability analysis is important to hydropower facilities such as spillway gates and turbines. This study investigated the application of reliability analysis methodology by 1) quantifying the system reliability for individual components, 2) conducting statistical analysis using historical performance data, and 3) fitting Weibull distribution to model the reliability. The analysis framework we outlined in this paper provides decision makers more information about operational risks for hydropower facilities. We have integrated the reliability based approach with a deterministic hydro system optimization model (OPT) to develop a reliability-based operation framework which formally treats risk and uncertainty in operations planning.

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