



Research papers

Multi-objective reservoir operation during flood season considering spillway optimization

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ARTICLE INFO

Article history:

Received 7 April 2017

Received in revised form 20 June 2017

Accepted 25 June 2017

Available online 12 July 2017

This manuscript was handled by A.

Bardossy, Editor-in-Chief, with the assistance of Sheng Yue, Associate Editor

Keywords:

Multi-objective reservoir operation

Spillway optimization

POA

Smooth support vector machine (SSVM)

Three Gorges Reservoir

ABSTRACT

Flood control and hydropower generation are two main functions of Three Gorges Reservoir (TGR) in China. In this study, a multi-objective operation model for TGR considering these two functions was developed. Since the optimal results of reservoir operation are mostly in the form of gross outflow which is hardly used to directly guide reservoir operation, the optimization of spillways operation was taken into account. For observed historical flood hydrographs and design flood hydrographs, the progressive optimality algorithm (POA) was employed to determine the optimal operation of spillways. For the real-time reservoir operation, a smooth support vector machine (SSVM) model was applied to abstract the optimal operation rules which consider the order and the number of spillways put into use. Results demonstrate that the use of different spillways has a significant impact on reservoir operation. Therefore, it is necessary to consider the order and number of spillways that should be used. Instead of optimizing outflow, direct optimization of the order and number of spillways can yield most reasonable results. The SSVM model simulates the relationship among inflow, water level and outflow satisfactorily and can be used for real-time or short term reservoir operation. Application of the SSVM model can also reduce flood risk and increase hydropower generation during the flood season.

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1. Introduction

Various flood control method was studied all over the world, one of which is establishment of reservoirs (Gomez-Ullate et al., 2010; 2011). Reservoirs are often operated with a number of purposes, which relate to environmental, economic and public services. Generally, these purposes include flood control, hydropower generation, navigation, sediment control, water supply, recreation, and fisheries, among which flood control and hydropower generation are two of the main functions for many of the reservoirs. Therefore, these two purposes were considered in this paper. During flood season, the most important function of reservoir is flood control. In the following, the importance and problems of flood control operation are discussed.

China is one of the countries most affected by natural disasters, especially flood disasters. The Yangtze River is the longest river in China and the third longest river in the world. Floods periodically occur in the Yangtze River basin in central and eastern China and cause considerable destruction of property and loss of life. Among

the most major floods are those of 1870, 1931, 1954, 1998, and 2010. The 1954 flood in the Yangtze River flooded an area of 193,000 km², killed 33,169 people, and forced 18,884,000 people to evacuate. In the Yangtze River basin, floods are caused by unusually high precipitation between June and August (Chen et al., 2015a,b,c; Zhou et al., 2015a,b). Summer is the main flood season due to the heavy monsoon rainfall (Chen et al., 2012). Floods in the middle and lower reaches of the Yangtze River mainly stem from the upper region of the Yichang Station, which is also the control station for the Three Gorges Reservoir (Chen et al., 2012; 2015a,b,c). Three Gorges Dam (TGD) project was started in 1994 and completed in 2009. The purpose for this dam includes flood control, power generation, navigation and tourism. However, the most important function of TGD is flood control, which is a major problem for the seasonal rivers of the Yangtze (Liu et al., 2015a,b). Millions of people live downstream of the dam, with many large, important cities like Wuhan, Nanjing, and Shanghai situated adjacent to the river. Plenty of farm land and China's most important industrial area are built beside the river. Therefore, flood control reservoir operation of TGD is an important research area.

Flood control reservoir operation in practice is influenced by many factors. Judicious operation of reservoirs is important during

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a flood. The operation of a flood control reservoir is normally accomplished using specific operating policies, or operating rules, which set forth the guidelines for making water release decisions under various hydrologic conditions (Zhou et al., 2015a,b; Liu et al., 2015a,b). The key variables governing the operation of flood control reservoirs are the available storage capacity and the expected inflow magnitude from an incoming flood. The purpose for flood control is to prevent flood damages downstream of the reservoir and the safety of the reservoir itself. Accordingly, releases are restricted by the maximum allowable non-damaging channel capacity at the downstream control points. Most studies on flood control reservoir operation focus on the optimal reservoir operation rules (Windsor, 1973; Reddy and Kumar, 2006; Wei and Hsu, 2008).

Few studies on flood control reservoir operation consider the real-time operation of spillway gates. The optimal control of spillways is also one of the most difficult problems in reservoir operation, since the optimal results of reservoir operation are mostly in the form of gross outflow which is hardly used to directly guide the reservoir operation. Karaboga et al. (2004) developed a model for real-time operation of spillway gates for a given incoming flood hydrograph. Later, Karaboga et al. (2008) presented another method for operation of spillway gates during a flood by a fuzzy logic model coupled with a tabu search algorithm. This study attempted to establish the optimal reservoir operation model, which considers the real-time operation of spillways. The operation constraints of spillways was also taken into account when establishing the reservoir operation model. The optimal operation schedule of spillways can be obtained directly based on an optimization technique.

In order to derive optimal operation rules, optimal algorithms need to be used. Various optimization models, such as linear programming (Wei and Hsu, 2008), dynamic programming (Chandramouli and Raman, 2001), genetic algorithms (Chang and Chen, 1998), and artificial neural network (Chandramouli and Raman, 2001) have been used for reservoir operation. Detailed reviews of these optimization techniques are also available in the literature (Wurbs, 1993; Rani and Moreira, 2010; Chandramouli and Raman, 2001). In order to deal with the dimensionality problem, the Progressive Optimality Algorithm (POA), proposed by Howson and Sancho in 1975 (Howson and Sancho, 1975), has recently been used for finding out the optimal or near-optimal solution (Liu et al., 2011). The significant advantages of POA over the above optimization techniques are as follows: (1) It avoids resolving the nonlinear objective functions and constraints in the solution procedure; (2) reduces the dimensionality difficulty by decomposing a multi-stage decision problem into a series of nonlinear programming two-stage problems; and (3) easily converges to the near-optimal solutions for complex problems (Guo et al., 2011). Therefore, in this paper, the POA method was used.

Operating rules are always identified using either fitting or simulation-based optimization methods (Rani and Moreira, 2010). In this study, the fitting method was used to identify the operating rules. Deterministic optimization techniques, such as POA, can be implemented to produce samples for fitting (Yeh 1985; Rani and Moreira, 2010). Support vector machine (SVM) is a new machine study method in the field of statistical learning theory based on Vapnik–Chervonenkis theory and structural risk minimization principle, and emphasizes studying statistical learning rules under small samples (Vapnik and Vapnik, 1998). SVM displays a lot of advantages and has been widely applied in many fields, such as classification, regression and prediction. This method has been used for reservoir operation. For example, Zuo et al. (2007) applied SVM to fitting reservoir operation function, and achieved good results. It is different from the artificial neural network model (ANN) based on empirical risk minimization.

SVM attempts to minimize the generalization error by seeking a right balance between the training error and the capacity of machine. With less model parameters, SVM has overcome the drawbacks of ANN in overfitting and complex model structure, and has been successfully applied to the classification and regression. Hence, SVM has become one of most successful tools for machine learning. However, SVM cannot efficiently deal with large data samples, and may be time-consuming and memory-consuming in calculation. Lee and Mangasarian (2001) developed an improved algorithm based on SVM, namely smooth support vector machine (SSVM), which transforms constrained quadratic optimization of SVM into non-constrained convex quadratic optimization and is better able to handle the cases of classification and nonlinear regression with a larger dataset. Lee et al. (2005) testified its superiority in solving by experimentation. Details of the algorithm were described by Mason and Tippet (2004). This article will use smooth support vector machine (SSVM) to mine the optimal operation rules of all kinds of spillways, and discuss its applicability and feasibility.

The objective of this study therefore was to establish the multi-objective reservoir operation rules during the flood season, considering the optimal operation of spillways. Two objectives were considered, including flood control and power generation. The fitting method was used to derive the operation rules. The POA technique was used to produce samples for fitting, and the SSVM model was applied to abstract the optimal operation rules which consider the order and the number of spillways put into use.

2. Study area

2.1. Introduction of the TGD

The TGD is a vitally important project for the development and harnessing of the Yangtze River (YR), and also the largest multi-purpose hydro-development project ever built in the world. TGR receives inflow from a drainage area of approximately 10^6 km^2 , with a mean annual runoff at the dam site of $4.51 \times 10^{11} \text{ m}^3$ (Chen et al., 2015a,b,c; 2016). Downstream from the TGR is the plain area of the middle and lower reaches of the Yangtze River, which is one of the most populous and developed areas in China and which also suffers from the most frequent and disastrous flood threats.

The TGR is a typical river channel type reservoir with a length of 660 km and a flood storage capacity of $22.15 \times 10^9 \text{ m}^3$, and plays a very important role in flood control of the Yangtze River. The Three Gorges Dam is the world's largest capacity hydroelectric power station with 34 generators, including 32 main generators, each with a capacity of 700 MW, and two power plant generators, each with a capacity of 50 MW, making a total capacity of 22,500 MW. Besides the comprehensive benefits from flood control and power generation, the TGR also improves the navigation conditions of the waterway in the reservoir area and downstream, and promotes the development of fishery as well as tourism.

Affected by monsoon climate and precipitation, 60%–80% runoff in a year concentrates in the flood season (from June 1 to September 30). During the flood season, flood control is the most important issue compared with other functions of the TGR. The flood control water level (FCWL) is the operation water level in the flood season in order to offer adequate storage for flood prevention (Chen et al., 2016). From June to September, the water level of TGR cannot always be higher than FCWL, because of the possible incidences of large floods (Chen et al., 2016). Therefore, during the flood season, huge amounts of flood waters have to be spilled through a number of hydraulic turbo generators and other spillways.

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