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Intelligent real-time operation of a pumping station for an urban drainage system

Nien-Sheng Hsu [a,*], Chien-Lin Huang [a], Chih-Chiang Wei [b]

[a] Department of Civil Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan
[b] Department of Digital Content Design and Management, Toko University, No. 51, Sec. 2, University Road, Pu-Tzu City, Chia-Yi County 61363, Taiwan

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SUMMARY

In this study, we apply artificial intelligence techniques to the development of two real-time pumping station operation models, namely, a historical and an optimized adaptive network-based fuzzy inference system (ANFIS-His and ANFIS-Opt, respectively). The functions of these two models are the determination of the real-time operation criteria of various pumping machines for controlling flood in an urban drainage system during periods when the drainage gate is closed. The ANFIS-His is constructed from an adaptive network-based fuzzy inference system (ANFIS) using historical operation records. The ANFIS-Opt is constructed from an ANFIS using the best operation series, which are optimized by a tabu search of historical flood events. We use the Chung-Kong drainage basin, New Taipei City, Taiwan, as the study area. The operational comparison variables are the highest water level (WL) and the absolute difference between the final WL and target WL of a pumping front-pool. The results show that the ANFIS-Opt is better than the ANFIS-His and historical operation models, based on the operation simulations of two flood events using the two operation models.

1. Introduction

A pumping station is the most important flood control facility of an urban drainage system, and its function is to drain urban rainwater to a river. When the water level of the river is higher than the level of the urban drainage system, the drainage gate of the pumping station is closed to prevent the river water from flowing into the urban drainage system. In such a situation, urban rainwater can only be drained by pumping; thus, the utilization of pumping machines in a pumping station when the drainage gate is closed is crucial to flood control. In recent years, rapid population increase, climate change, and urbanization have decreased the surface permeable area and time of concentration in metropolitan areas. Additionally, the drainage system in Taiwan is insufficient, which causes the water level to rise extremely quickly during typhoons and heavy rainfall. Furthermore, the discharge of a pumping station is dispersed, unlike a reservoir, in which the discharge is continuous. Owing to these conditions, the water level of an urban drainage system is difficult to control during flood periods, in comparison to that of a reservoir. Traditionally, decisions are made about the operation of a pumping station solely on contrived subjective evaluations based on the observed current water level of the pumping front-pool and precipitation. Such evaluations may be subject to uncertainty and erroneous probability. To optimize the operation of the pumping station and reduce erroneous probability, the development of intelligent, real-time pumping station operation models for flood control is necessary and important.

System analysis is the most effective decision-making method in water resources planning and management. Traditionally, the tools for system analysis are classified as optimization and simulation methods. Optimization methods produce better solutions and have therefore been widely used for water resources system analyses in recent years. Researchers, including Windsor, 1973; Unver and Mays, 1990; Niewiadomska-Szynkiewicz et al., 1996; Chang and Chen, 1998; Needham et al., 2000; Hsu and Wei, 2007; Valeriano et al., 2010; and Kumar et al., 2010, have applied optimization techniques to reservoir operation for flood control. During flood control periods, the major facilities for preventing disasters due to flood include reservoirs and pumping stations. Regarding the use of pumping stations, previous studies have used only simulation methods for constructing operation or inundation models and for discussing the operation outcomes of various models. Some examples of such studies are given here. Hsu et al. (2000) developed an urban inundation model that combines a storm sewer model, a two-dimensional diffusive overland-flow model, and the operation of pumping stations to simulate urban inundation caused by the discharge of storm sewers and outlet pumping stations. Chang et al. (2008) used a counterpropagation fuzzy-neural

* Corresponding author. Tel.: +886 2 33662640; fax: +886 2 33665866.
E-mail address: nsshue@ntu.edu.tw (N.-S. Hsu).

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network (CFNN) to obtain fuzzy information about flood control, the validated portion of which were used to simulate historical operation strategy in an urban storm flood control system. Chiang et al. (2011) used an adaptive network-based fuzzy inference system (ANFIS) and a CFNN for on-line prediction of the number of open and closed pumps at a pivotal pumping station up to a lead-time of 20 min. Considering the abovementioned details, this study concluded that the real-time operation of pumping station using optimization methods has not yet been studied.

Additionally, studies on combining fuzzy theory and artificial neural networks for flood control have increased in popularity in recent years, and previous studies have proven that the models can be effectively used to achieve real-time operation of reservoirs. Bagis and Karaboga (2004) proposed a new and efficient control method based on fuzzy logic for real-time operation of the spillway gates of a reservoir during floods of any magnitude. Yu et al. (2004) proposed a multi-person multi-objective decision-making model for flood control operation using fuzzy theory. The model considers the effect of multiple objectives and the experience and knowledge of the decision makers. The results show that this model is simple and more adaptable to practical problems. Chang et al. (2010) established an intelligent real-time fuzzy reservoir flood control model (IFFCM) for ensuring reservoir safety and storing floodwaters for future use. The IFFCM was first constructed by extracting information from the optimal operation hydrographs of typhoon events obtained using a genetic algorithm (GA), and then, the reservoir release was inferred using an ANFIS. The results showed that the proposed model performs significantly better than historical reservoir operations; effectively reduces the downstream peak flood stage; and stores floodwaters for future use. Wang et al. (2011) presented a decision model for flood control operations based on the theory of variable fuzzy sets. The model incorporated the knowledge of the operator about flood operations, and the results showed that it is flexible and practical. Based on the above literature review, we can conclude that an ANFIS has the ability, mechanism, and structure for intelligent thinking, analysis, and inference similar to that of a human. In addition, the application of an ANFIS to flood control reduces the processing time for real-time optimization and helps to meet the operation goal. Hence, the application and development of this method is worth investigating.

In this study, we use artificial intelligence techniques to develop two real-time pumping station operation models of an urban drainage system for flood control. The purpose of the models is the determination of the real-time operation criteria of pumping machines during periods when the drainage gate is closed. Finally, we compare the advantages and disadvantages of the models using the results of simulations of historical flood events.

2. Method development

In this study, we develop a four-part procedure to achieve the research objective, as shown in Fig. 1. Each step is described below.

Step 1: Acquire the input and decision information of the pumping station operation models, which include the monitored meteorology, hydrology, and pumping machine operation information before the current time (t).

Step 2: Enter the monitored information into the two pumping station operation models, the ANFIS-His and ANFIS-Opt, to determine the real-time number of open pumping machines. The ANFIS-His is constructed from an ANFIS using historical operation records, which is described in steps 2–3; whereas the ANFIS-Opt is constructed from an ANFIS using the best operation series obtained by an optimization model, which is described in steps 2-1 and 2-2. The three sub-steps are here described.

Step 2-1: Construct the optimization model of the pumping station operation.

Step 2-2: Optimize the operation series and obtain the associated front-pool water level using the historical meteorology data series for each flood event as the operation target, and then apply the ANFIS to construct the operation model for evaluating the real-time operation of the pumping machines after training and validation.

Step 2-3: Adopt the historical operation of the pumping machines using the meteorology and hydrology data series of historical flood events as the operation target, and apply the ANFIS to construct the operation model for evaluating the real-time operation of the pumping machines after training and validation.

Step 3: Compute the front-pool water level after operation at time t by using the ANFIS-His and ANFIS-Opt to simulate the operation of the subsequent time ($t + 1$). The water level can be simulated using the mass balance equation of the front-pool along with the pumpage and inflow. The pumpage can be computed from the number of open pumping machines and the pumpage characteristics curve; the inflow can be calculated from the mass balance equation together with the historical pumpage, the front-pool storage transferred by the *H–S Curve* (water level-storage relationship equation), and the water level (step 3-1). If the operation reaches the flood duration (T), terminate the operation simulation.

Step 4: Compare the operation results and assess the developed models.

2.1. Optimization model for the operation series

2.1.1. Construction of optimization model

When the lift height of a pumping machine increases, the pumpage decreases when the pump is opened. Additionally, when the front-pool inflow increases, the front-pool water level reduces at a lower rate. Hence, if the goal is to effectively reduce the front-pool water level, it is important to determine the optimal pumping timing and pumpage. The best operation strategy is to begin pumping before the peak inflow, which would increase the storage capacity and drainage capability of the drainage system. By this process, the front-pool water level can be effectively reduced. Reducing the highest front-pool water level decreases the inundation risk, especially in the low-lying regions of an urban basin. In current practice, pump operators seldom consider this as the best strategy because it is difficult to implement from an operational viewpoint. Furthermore, the final front-pool water level should be the indicator of when to begin flood control at the end of flood events. By this process, the drainage operation of pumping machines can be safely concluded. In addition, the operational costs at the pumping station include the cost of repairing the pumping machine and the cost of pumping. Pumping station operators are concerned about the damage of pumping machines that can result from frequent opening and closing, with repair cost sometimes exceeding USD 30,000 per machine. In practice, a pumping machine driven by electric power or diesel fuel needs to be opened only for a few hours during a flood event. Therefore, the pumping cost is considerably lower than the repairing cost and the inundation loss caused by insufficient pumping. Hence, this study does not consider pumping cost as the objective function. To consider the abovementioned operational objectives, we developed a real-time operation optimization model for pumping machines that includes three weighted objective functions: (1) minimizing the highest front-pool water level of the pumping station during a flood event; (2) minimizing the absolute difference between the final and target front-pool water levels ($|\triangle H_{final\text{-}target}|$); and (3) minimizing the number of open and closed pumping machines during