Canal Operation Simulation of Middle Route Project

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ABSTRACT: Middle Route Project, the largest water conveyance system in China delivers the water of Changjiang River to North China. In order to create canal operation simulation system, mathematical models are established based on the analysis of hydraulics about steady flow, unsteady flow, and check gate. By simulating the canal operation behavior, we improved the check gate control algorithm and predicted the change process of water surface and flow profile which is very valuable to actual canal operation.

1 INTRODUCTION

South-to-North Water Diversion Project is the largest and most expensive water transfer project in China. The general layout of the project includes three routes: Western Route Project (WRP), Middle Route Project (MRP) and Eastern Route Project (ERP), which will divert water from upper, middle, and lower reaches of Changjiang River respectively, to meet the developing requirements of Northwest and North China. For MRP, the 1432 km long aqueduct has the capacity to transport 9.5 billion m^3 of Hanjiang River water from Danjiangkou Reservoir to the north cities of China such as Beijing and Tianjin.

The design discharge of MRP main aqueduct is 350~50m^3/s, design water depth is 8~3.8m, bottom width is 29.0~7m. Water is transferred by gravity along the route. Construction of the project was started in 2003 and planned to be completed in 2010, the budget is 130 billion RMB.

2 CANAL HYDRAULICS

2.1 Steady Flow

Steady Flow includes uniform flow, gradually varied flow and rapidly varied flow. Steady, gradually varied flow is an important flow condition in canal operation. It is formed upstream of check structure. In this case, it is known as the backwater profile, which can be generated through energy equation:

$$z_1 + \frac{\alpha_1 {v_1}^2}{2g} = z_2 + \frac{\alpha_2 {v_2}^2}{2g} + h_{w1-2} \qquad (1)$$

with: z = water level of cross section(m), v = average velocity (ms^{-1}), α = velocity coefficient, h_{w1-2} = head loss(m).

2.2 Unsteady Flow

Unsteady, gradually varied flow is also an important flow condition in canal. For example, check gate movement produces changes in flow and in adjacent depths, the change takes the form of traveling translatory waves which propagates in an open channel and results in displacement of water particles in a direction parallel to the flow. The physical dynamics of unsteady gradually varied flow can be correctly approximated by Saint-Venant's equations which are nonlinear partial derivative hyperbolic equations. Saint-Venant's equations include comprise mass equation and momentum equation. These equations are:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial s}=q \tag{2}$$

$$\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{2Q}{gA^2}\frac{\partial Q}{\partial s}+\frac{\partial z}{\partial s}=-S_f \tag{3}$$

with: A = cross section area (m^2),t = time (s), Q = discharge(m^3s^{-1}), s= longitudinal abscissa (m), in the direction of the flow, q = lateral inflow or outflow (m^2s^{-1}), g = 9.81 ms^{-2}, z =water surface absolute elevation (m), $S_f=\frac{n^2Q^2}{A^2R^{4/3}}$, friction slope, n = Manning coefficient, R = hydraulic radius (m).

These equations must be completed by external and internal boundary conditions at check structures, where Saint-Venant's equations are not valid, and by initial conditions. We solve these equations by implicit finite difference method, which is also named Preismann Method. Figure1 shows the calculation gird of Preismann Method.

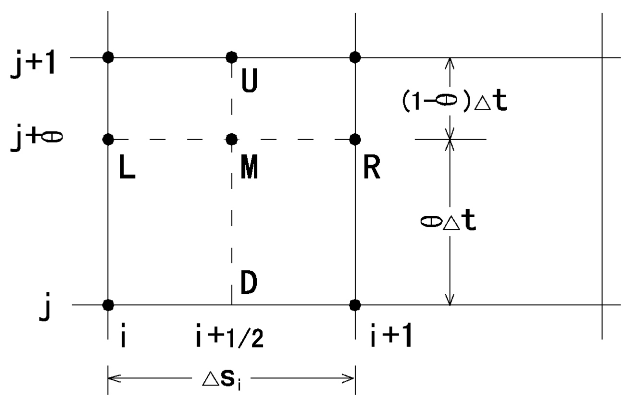

Fig. 1 implicit finite difference grid

In most case, coefficient θ is between 0.7 and 0.75.

2.3 Check Structures

Canal control structures regulate the flow and depths of water. The most common type of canal control structure is the check structure. The canal check gate structure has become the dominant tool for implementing canal system operations. Depending on the type of check structure and hydraulic conditions, there are different forms of check structures equations, such as Weir-Free flow, Weir-Submerged flow, Gate-Free flow, Gate-Submerged flow. We've tried some of them, in most case we use Gate-Submerged equation:

$$Q = C_d ab\sqrt{2gh_1} \tag{4}$$

with: C_d = flow coefficient, a function of h_1, h_2 and a, a = device opening (m), b = device width (m), h_1 (resp. h_2) = upstream (resp. downstream) water depth (m).

3 OPERATION METHOD

The method of operation determines how the water level varies in a canal pool to satisfy the operation concept. A canal's recovery characteristics-the speed and manner in which the canal recovers to a new steady-state flow after a flow change-are dependent upon the method of operation. The methods of operation are:

1. Constant downstream depth
2. Constant upstream depth
3. Constant volume
4. Controlled volume

The "Constant downstream depth" method is very prevalent because a canal can be sized to convey the maximum steady flow, steady-state water depths should never exceed the normal depth for the design flow. The canal prism size and freeboard can be minimized, thus reducing construction costs.

The "Constant upstream depth" method need canal banks to be horizontal to accommodate the zero-flow profile, which increase the cost of construction considerably. Most existing canals could not use this method.

The "Constant volume" method is based upon maintaining a relatively constant water volume in each canal pool at all times. The main advantage of constant volume method is the ability to quickly change flow conditions in the entire canal system. One disadvantage of constant volume method is the additional canal bank and lining required at the downstream end of each pool.

The "Controlled volume" method offers the most flexibility of any method of operation. Canal operation can adapt more easily to normal, abnormal, and emergency conditions. Operational flexibility primarily is restricted by depth fluctuation limits.

The selection of canal operation method is related to canal delivery concept. The main delivery concept in MRT is one in which water delivery is scheduled based upon advanced notification. Individual water users order water by specifying the time of delivery and the quantity of water they wish to receive. Then, individual water orders are compiled to predict the required canal-side turnout flow changes. All turnout flows are added up to obtain the total flow schedule for the canal. A canal system is easier to operate when deliveries are scheduled in advance. Main canal flow changes are predictable and normally can be accomplished without major water level fluctuations. An operation that minimizes water level fluctuations decreases the potential for canal lining and embankment failures.

Most pools in MRT are designed to utilize the “Constant downstream depth” method. The constant downstream depth method of operation is particularly effective when combined with the scheduled delivery concept. Any steady-state water depths should never exceed the normal depth for the design flow which is very important for the safety of canal operation.

Some special pools utilize the “Controlled volume” method. The pool of “cross Yellow River” in MRT is one of them. For design flow discharge, the head loss of the “cross Yellow River” pool is about 6m, which makes the utilization of “Constant downstream depth” method impossible. So we give different downstream depths for design flow and zero flow. The target depth of downstream alters between the 2 depths with the target flow discharge. That means the volume of the pool is controlled to satisfy canal operation demand.

4 CANAL OPERATION SIMULATION

Canal operation simulation system is a series of hydraulic models that generate schedules for check gates based on the initial conditions of the aqueduct, the water delivery schedule, and the availability of the pumps and gates in the system. The system consists of five interconnected model: 1) data input model; 2) steady flow model; 3) unsteady flow model; 4) gate operation strategy model; 5) gate discharge calculation model; 6) date output model.

4.1 Data Input Model

The data input file should include all information needed in the simulation of the canal. Usually, it consists of 3 parts:

1) Boundary Conditions of Simulation

Four boundary conditions of canal operation simulation are needed: 1) The water depth assumed to be constant before the first check gate of the canal; 2) The water depth assumed to be constant behind the last check gate of the canal; 3) Initial discharges of every check gate and turnout; 4) Final discharges of every check gate and turnout.

2) Geometrical Parameter of the Canal

According to section geometry characteristic, the whole canal is divided to many sub-canals. Sub-canal includes gradual change section, aqueduct, siphon, tunnel, check gate, wasteway gate etc. Some information items of sub-canal are the same, such as station, length, bottom width, bottom altitude, side slope, roughness, and name. Some information items are related to sub-canal property. For example, hole amount for aqueduct, siphon, tunnel and check gate; hole height for siphon; bottom width change for gradual change section; design flow for wasteway gate etc.

3) Operation Parameter of the Check Gate

There should be many check gates along the canal (for example, there are 62 check gates along Middle Route Project), every gate has particular characteristic. So we should input the parameter of the check gate before simulation. They are design discharge, design water level, initial water level before the gate, final water level before the gate, minimum movement of the gate, permitted drawdown rates, other control parameters etc.

4.2 Steady Flow Model

The purpose of steady flow model is to generate water surface and flow profile of canal as the initial condition and final condition of canal operation simulation. The program is based on steady flow hydraulics in chapter 2.1.

4.3 Unsteady Flow Model

Unsteady flow model was developed to simulate canal state behavior change during operation process. We can work out the water surface and flow profile of next time step based on the water surface and flow profile now and boundary condition of next time step. The principle of unsteady flow calculation is listed in chapter 2.2. Actually, unsteady flow calculation is only used in simulation. In real operation, there should be many observation points along the canal, we can generate the water surface and flow profile of every time step not by unsteady flow calculation, but by reading the telemetry.

4.4 Gate Operation Strategy Model

Gate operation strategy model is the essential part of canal operation control. It is within this model that the control philosophy of operation is implemented. The primary purpose of Gate Operation Strategy Model is to generate check gate movement schedules so that each pool maintains its target water level.

Logic of control is the heart of the model. The MRP simulation system uses a combination of feedback control and feedforward control as the control algorithm. In the feedforward control algorithm, discharge is the controlled variable. Beginning at the downstream end of the canal, the discharge schedule for each check gate and turnout is generated based on inherent system time delays compensation and turnout requirement. The operation process should implement the schedule, so that roughly check gate movement instruction is generated. The instruction should be modulated by feedback control logic. Water level is the controlled variable of feedback control. Every period of time, the water levels before and behind the check gates are measured, the deviation from the target is fed back into the control algorithm in order to produce a corrective instruction to the check gate.

Of course, gate operation strategy not only includes control algorithm, but also includes some operation experiential rules that approved to be effective in operation practice. For example, not move a check gate too much a time.

4.5 Gate Discharge Calculation Model

Gate discharge calculation model consists of a series of methods based on different flow condition. They are used in two ways: 1) Calculate the discharge of the gate according to water level and gate-opening; 2) Calculate the gate-opening according to water level and target discharge.

4.6 Date Output Model.

Date output model can analyze simulation data, write the data into output file and draw plots. Usually, 3 output files are generated in the model: 1) Steady flow result; 2) Unsteady flow result; 3) Operation process analysis result. Of course, after the operation simulation, we can get many results data according to the requirement.

5 SIMULATION OF MRP OPERATION

The goal of the simulation is to develop improved designs and operational methods. MRP is more than 1,400km long with 62 check gates along the route. We created the simulation program, and tried the operation simulation on three conditions:

5.1 Normal Operation (Increasing Discharge).

The flow was increased from $0m^3/s$ to design discharge $350m^3/s$ at the beginning of the canal. The result shows all pools could reach respective target water level and the volume of the canal increased about 30 million m^3. The water depth did not exceed design depth, the canal operates safely. It took 130h to accomplish the discharge increasing process.

5.2 Normal Operation (Decreasing Discharge).

The flow was decreased from $350m^3/s$ to $0m^3/s$ at the beginning of the canal. The result shows all pools could reach respective target water level and the volume of the canal decreased about 30 million m^3. The water depth did not exceed design depth, the canal operates safely. It took 300h to accomplish the discharge decreasing process.

The reason why discharge-decreasing condition is much longer than discharge-increasing condition is the drawdown criteria. Rapid increases in water depth are seldom a problem unless the maximum depth is exceeded. However, rapid decreases can damage the canal even when depths remain within an acceptable range. A maximum acceptable drawdown rate should be established for each canal. Typical drawdown rates permitted in MRP are 0.3m during any 24-hour period. In constant downstream depth operation method, the water level increases with discharge increasing, but it decreases with discharge decreasing. So the time of the two normal operations is much different.

5.3 Emergency Flow Stoppage

Preliminary investigations using the gate emergency algorithm yielded a procedure to stop the canal flow as quickly as possible. In emergency condition, there is no constrain of drawdown rate, but waves generated in shut down of flow can not exceed the freeboard.

We simulated the condition that the flow was shut down from design discharge to zero. Flow in the entire canal could be stopped in 2hours. But some wasteway gates should be opened to let out excess flows. Wasting is an undesirable loss of a valuable resource, it prevents water from being used for the intended purpose. In most canals, wasting water is unintentional during normal operations and is avoided whenever possible. However, by sacrificing some water, wasting can be a valuable operational tool during emergencies to prevent more detrimental consequences.

6 CONCLUSIONS

By the simulation of MRP operation, response characteristics of a water system is investigated, which is essential to integrate canal design with the control method. The simulation is a test of check gate control algorithm, and the result provides much useful information to improve canal designs and operational methods.

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