RELATIONSHIP OF OPERATION STABILITY AND AUTOMATIC OPERATION CONTROL METHODS OF OPEN CANAL

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ABSTRACT

Water level in open canal fluctuates with the change of the discharge. The water flow from one steady state to another will take a period of time. For a certain canal, the process of the dynamic response is affected by using different automatic control methods. In order to shorten the response time and limit the fluctuating range of water level, maintain the performance of automatic control canal system stability, proper automatic canal control methods should be adopted. In this study, taking the middle route of China's South-to-North Water Diversion Project as an example, the relationship of operation stability and automatic control methods of open canal is studied by means of numerical simulation of unsteady flow in open canal with different control methods, and some useful results on the automatic canal control system of the middle route of Chinese South-to-North Water Diversion Project are obtained.

INTRODUCION

To deliver the appropriate amount of water to a user at the appropriate time, the performance of irrigation water delivery canal systems with automatic control should maintain stability. Water level in open canal fluctuates with the change of the discharge. The water flow from one steady state to another will take a period of time. For a certain canal, this process is affected by the canal operation control methods, range of discharge change and rate of it. In order to shorten the response time and limit water level fluctuating range, maintain the performance of automatic control canal system stability, proper automatic canal control methods should be adopted.

The middle route of China's South-to-North Water Diversion Project is the longest distance open canal with flat slope and very large design discharge, but lacks necessary in-line water storage. To improve the flexibility of water delivery while also maintaining the performance stability, automatic control methods should be studied and well-chosen. In this study, taking the middle route of China's South-to-North Water Diversion Project as an example, the relationship of operation stability and automatic control methods of open canal is studied by means of numerical simulation of unsteady flow in open canal with different control methods, and some useful results

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on the automatic control system of the middle route of China's South-to-North Water Diversion Project are obtained.

NUMERICAL SIMULATION OF AUTOMATIC OPERATION CONTROL CANAL

Numerical simulation model of automatically control canal is composed of control algorithm of the controller and hydraulic equations of the transient flow in canal.

One-dimensional Unsteady Non-uniform Flow in Open Canal

Equations Generally, the Saint Venant equations are used to define one-dimensional unsteady non-uniform flow in open canal. The Saint Venant equations, which consist of a continuity equation (Equation (1)) and a momentum equation (Equation (2)), can be expressed as (Xu Zhengfan, 1986):

$$B\frac{\partial z}{\partial t}+\frac{\partial Q}{\partial s}=q \tag{1}$$

$$\frac{\partial Q}{\partial t}+2v\frac{\partial Q}{\partial s}+(gA-Bv^2)\frac{\partial z}{\partial s}=Bv^2(i+M)-g\frac{Q^2}{A^2C^2R} \tag{2}$$

Where B is the width of canal water surface(m); z is the water surface elevation(m); t is the time(s); Q is the discharge(m^3/s); C is the Chezy coefficient; s is the distance along the canal(m); q is the inflow along the canal side(m^3/s/m); g is the gravitational acceleration(m/s^2); A is the cross-sectional area(m^2); v is the flow velocity along canal axes of the canal side inflow(m/s), R is the hydraulics radius(m); i is the canal bottom slope; $M=\frac{1}{B}\cdot\frac{\partial A}{\partial s}\Big|_h$.

Solution of The Saint Venant Equations The Preissmann implicit scheme is widely adopted as the numerical solution method of Saint Venant equations for its fine characteristics such as high accuracy and unconditional convergence. In this method, the s-t plane of solution domain is divided into a regular rectangular net, then difference quotients are used to approach the partial derivatives of dependent variables (Z and Q). The following discrete equations on each grid can be deduced:

$$a_{1i}Z_i^{j+1}-c_{1i}Q_i^{j+1}+a_{1i}Z_{i+1}^{j+1}+c_{1i}Q_{i+1}^{j+1}=e_{1i} \tag{3}$$

$$a_{2i}Z_i^{j+1}+c_{2i}Q_i^{j+1}-a_{2i}Z_{i+1}^{j+1}+d_{2i}Q_{i+1}^{j+1}=e_{2i} \tag{4}$$

Where $a_{1i} = 1$; $c_{1i} = 2\theta \frac{\Delta t}{\Delta s_i} \frac{1}{B_M}$; $e_{1i} = Z_i^j + Z_{i+1}^j + \frac{1-\theta}{\theta} c_{1i} (Q_i^j - Q_{i+1}^j)$;

$a_{2i} = 2\theta \frac{\Delta t}{\Delta s_i} ({V_M}^2 B_M - gA_M)$; $c_{2i} = 1 - 4\theta \frac{\Delta t}{\Delta s_i} V_M$; $d_{2i} = 1 + 4\theta \frac{\Delta t}{\Delta s_i} V_M$;

$$e_{2i} = \frac{1-\theta}{\theta} a_{2i} (Z_{i+1}^j - Z_i^j) + [1 - 4(1-\theta)\frac{\Delta t}{\Delta s_i} V_M] Q_{i+1}^j + [1 + 4(1-\theta)\frac{\Delta t}{\Delta s_i} V_M] Q_i^j$$
$$+ 2\Delta t {V_M}^2 \frac{A_{i+1}(Z_M) - A_i(Z_M)}{\Delta s_i} - 2\Delta t \frac{gn^2 {Q_M}^2 {P_M}^{4/3}}{{A_M}^{7/3}}$$。

Where the hydraulics parameter of the center difference $\varphi_M = \theta(\frac{\varphi_i^{j+1} + \varphi_{i+1}^{j+1}}{2}) + (1-\theta)\frac{\varphi_i^j + \varphi_{i+1}^j}{2}$,

φ refers to the water surface elevation Z, the discharge Q, the velocity V, the water surface width B, the cross-sectional area A or the wetted perimeter P; the subscript i is the space layer serial number, the superscript j is the time layer serial number, θ is the weight factor (usually choose from 0.7~0.75).

Combining all the equations, a set of large-scale sparse nonlinear equations which can be solved by double elimination methods (recursion methods) are obtained.

Control Algorithm

A control algorithm is a prescribed set of well defined rules or processes for the solution of a problem in a finite number of steps. The algorithm is designed to process the input information from the sensors, perform the comparator function, and calculate the proper output to the actuator. The input is quantities of parameters those are observed, measured, or predicted such as water levels; the output is a control action such as gate movement. Control algorithm can be translated to a computer program and executed by computer. In this study, control effect is compared between two different control algorithms. One is the Proportional+ Proportional plus Reset control (P+PR), another is Linear Quadratic Regulator control (LQR).

P+PR Control The incremental P+PR control algorithm can be described as follow:

$$\Delta G(k) = K_P[e(k) - e(k-1)] + K_I e(k) = K_P \Delta e(k) + K_I e(k) \quad (5)$$

Where ΔG is the output of feed-back control; K_p is the proportional coefficient; K_I is the integral coefficient; e is the difference of water levels; Δe is described by $\Delta e(k) = e(k) - e(k-1)$;

k is the sampling time.

Block diagram of P+PR control is shown in Figure 1.

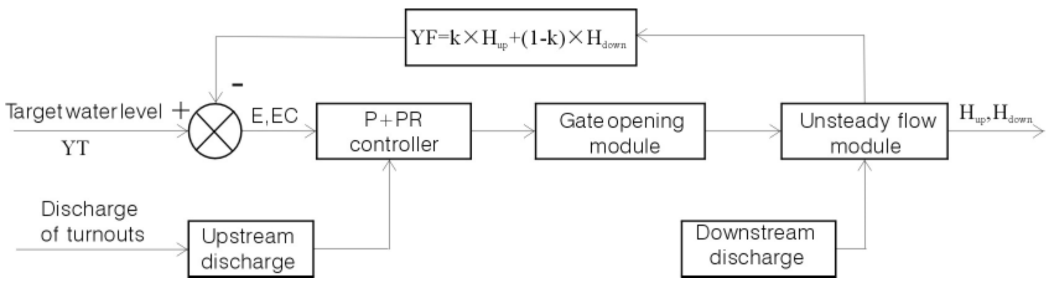


Figure 1. Block Diagram of P+PR

The target level YT in Figure 1 can be upstream water level, downstream water level or weighted value of both. When the weighting factor K is equal to 0， the operation method is upstream control. When K equal to 0.5, it is constant volume control.

<u>LQR Control</u> LQR control is based on state-space theory. In this study, the Saint Venant continuity equation and momentum equation is first discretized by the Preissmann implicit scheme, and equations that have been discretized are expanded in Taylor series at each equilibrium point. Taking only the linear terms, omitting the higher terms, the linear discrete-time state-space model can be deduced as follow (Zhao Wenfeng, 2002):

$$\delta x(k+1) = \Phi \delta x(k) + \Gamma \delta u(k) + \Psi \delta q(k) \tag{6}$$

where $\Phi = (A_L)^{-1} \times A_R$ is a $l \times l$ feedback matrix; $\Gamma = (A_L)^{-1} \times B$ is a $l \times m$ control matrix; $\Psi = (A_L)^{-1} \times C$ is a $l \times p$ disturbance matrix; $\delta x(k)$ is a $l \times l$ state vector; $\delta u(k)$ is a $m \times l$ control vector; $\delta q(k)$ is a $p \times l$ disturbance vector; l is the number of state variable; m is the number of control variable (gate number); k is the sampling number; p is the number of turnouts. The value of matrix Φ, Γ, Ψ is obtained by the operation state of the canal system.

Define output equations as $\delta y(k) = H\delta x(k)$, where H is the output matrix. Then the output (i.e., upstream and downstream water levels, discharges of the canal) can be obtained from the state vector δx.

The water level and discharge can be used as state vectors, gate position and discharge of turnouts is used as boundary conditions, then state-space model of the canal can describe the whole spatio-temporal hydraulic response of the operation of canal. Then, the change of the canal water levels can be translated into the transfer of state variables of the state-space model. LQR belongs to the optimization techniques which have been applied to control problems in an attempt to simplify the tuning process. In a linear response model, the controller can be tuned by minimizing a quadratic performance indicator or objective function. LQR can be used to determine the appropriate values for the non-zero constant gain matrices. In LQR theory, the gain matrix is chosen so that the value of the objective function is minimized. The objective function is a performance index of the controller and is a quadratic function of the state vector and the control actions.

Numerical Simulation of Multi-pool Canal System

From the analysis of gate operation technique, it is known that the response time is shortest if technique of synchronous gate operation is used in multi-pool canal (Bureau of Reclamation, 1991). So the technique of synchronous gate operation is used to realize computer centralized control in multi-pool in this study.

In computer centralized controlled multi-pool canal system, the water level sensor converts parameters such as upstream and downstream water level of each pool to the control system, immediately the gate sensor provides the gate position to the control system. The data form sensor will be classified, stored and manipulated by centralized control system. When the water delivery is changed, the centralized control system will adjust the positions of check gates to ensure the anticipative discharge using the technique of synchronous gate operation after computing the input parameters from the sensors. In the process of control, the system collects the input parameters and revises the output parameters frequently. The block of mathematical simulation of a multi-pool canal system is shown in Figure 2.

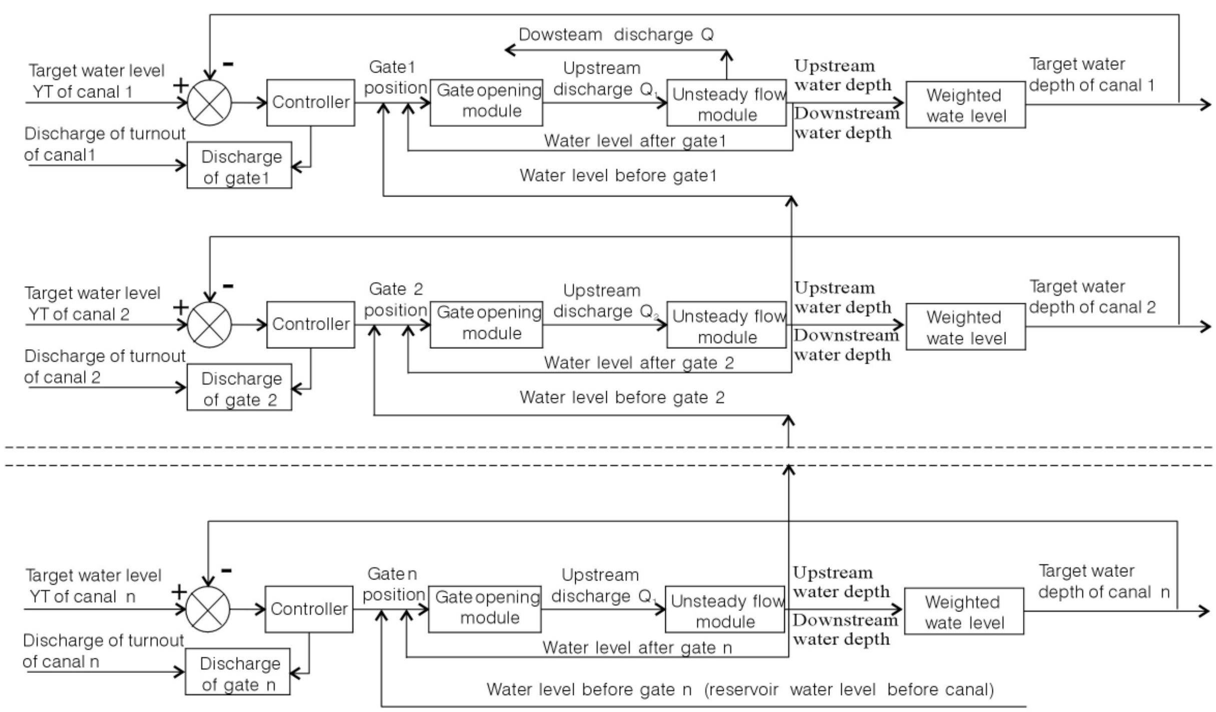


Figure 2. Block of Numerical Simulation of Multi-pool Canal System

ANALYSIS OF OPERATION STABILITY AND AUTOMATIC CONTROL METHODS ON TEST CANAL

Test Canal

The discharge and the range of discharge change at the beginning part of middle route of China's South-to-North Water diversion Project is the largest. The canal of this part is chosen as test canal to simulate the hydraulic response of the canal in several control methods. The characteristics of the test canal are: bottom width is 40m, side slopes is 3, Manning n is 0.015, bottom slope is 0.00004, design flow is 600m^3/s, giving a design water depth of 7.47m. The number of pools in test canal is three.

Relationship of Stability and Operation Methods

A canal's dynamic response is mostly dependent upon the method of pool operation. The method of operation is based upon the location of the canal pool water surface pivot point. There are four operation methods. Which are constant downstream depth, constant upstream depth, constant volume and controlled volume (Pierre. O. M., 1998).

In the constant upstream depth method of operation, the water depth at the upstream end of each canal pool remains relatively constant. The constant depth method is sometimes called "level bank" operation, because canal banks must be horizontal to accommodate the zero-flow profile. For cost of construction of a level bank canal is huge, this method is rarely adopted.

In the constant downstream depth method of operation, a constant downstream depth is maintained by pivoting the water surface at the downstream end of the canal pool as shown on Figure 3. This method is used in most canal systems. The primary reason why this method is so prevalent is that 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 rate. The canal prism size and freeboard can be minimized, thus reducing construction costs.

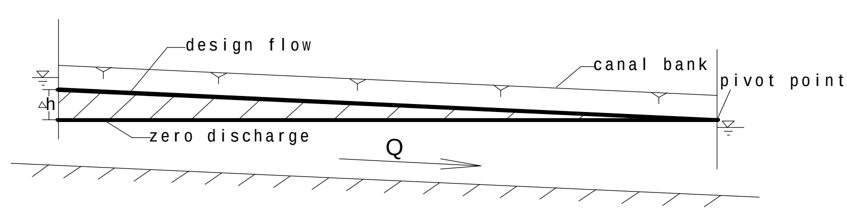


Figure 3. Constant Downstream Depth Method of Operation

The constant volume method of operation is based upon maintaining a relatively constant water volume in each canal pool at all times. The water surface will pivot about a point near midpool as the flow changes from one steady state to another as shown on Figure 4. Additional canal bank and lining is required at the downstream end of each pool, as compared to a conventional canal bank. However, the additional height required to accommodate the zero-flow water surface is only about one-half that required for level bank operation.

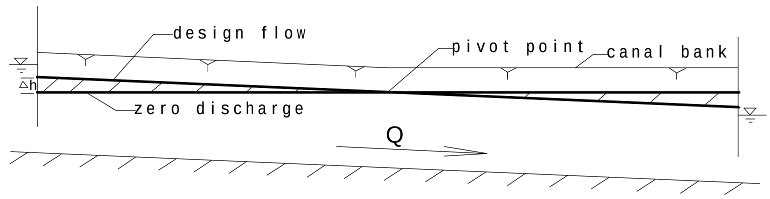
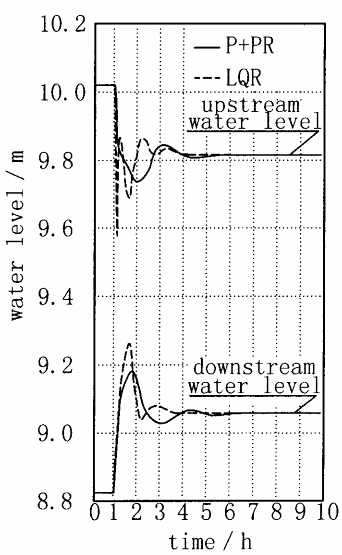


Figure 4. Constant Volume Method of Operation

The controlled volume method of operation is operated by managing the water volume contained in one or more canal pools. Volume can be changed to satisfy operational criteria by allowing the pivot point to move within each pool. This method required using the supervisory control method and possible need for greater freeboard or a large canal prism cross section in order to obtain a big volume.

In large-scale water transfer projects, the constant downstream depth and constant volume are often used (Wu Zeyu, 2005). Thus, this study compares the two methods only. In this case, the length of each pool is 30km. Initially, the canal flow is decreased from 600m^3/s to 480 m^3/s at 1 hours. The simulation results of pool 2 (middle pool) is shown in Figure 5, Figure 6 and table 1(using P+PR controller).



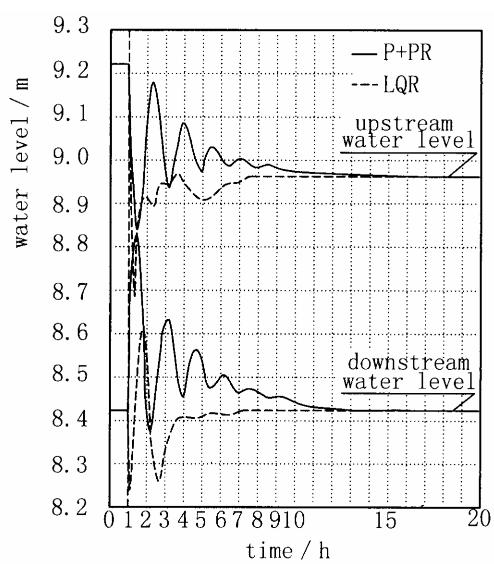


Figure 5. Constant Downstream Depth Figure 6. Constant Volume

Table 1. Hydraulic Response of the Canal 2 in Different Operation Methods

Operation methods	Position of water level	The largest variation range of water level	The most rapid drawdown	Hydraulic response time
Constant volume	Water level at upstream end of pool 2	0.281m	0.28m/h	5.6h
	Water level at downstream end of pool 2	0.356m	0.152m/h	6.2h
Control downstream depth	Water level at upstream end of pool 2	0.382m	0.787m/h	15.1h
	Water level at downstream end of pool 2	0.451m	0.338m/h	13.9h

The results show that the constant volume method of operation is better than constant downstream depth method in hydraulic response not only with P+PR controller, but also with LQR controller. The difference between constant volume and constant downstream depth is the position of pivot point (water level control point), it is shown as Figure 3 and Figure 4. For the reason that the pivot point is in the middle of pool, the time that the upstream and downstream wave comes to the control point with constant volume is shorter than with control downstream depth. Therefore, the hydraulic response with the constant volume is better than control downstream depth.

Relationship of Stability and Control Methods

Controller In this study, two typical controllers is compared. One is the P+PR controller of model basing on traditional control theory. Another is the LQR controller of a model basing on modern control theory. The result is shown in Figure 5 and Figure 6.

The result show that the two controllers basing on different control theory can both be used to the automatic control of canals, but the two kinds of controllers is each from different characteristics. The response time of LQR is shorter than P+PR, but the variation range of water level of LQR is bigger than P+PR. Compared with P+PR control model, the LQR control model in this study is more complex and can't to deal with the case of big flow change for the reason that the equations are disposed at each equilibrium point linearity. The P+PR control model in this study is credible and can be used to most case.

Flow Change Rate and Pool Length Drawdown (drawdown is the rate of depth reduction at any point in the canal) is influenced not only by methods of operation, but also by the flow change rate and pool length. In this study, three different flow change rate (canal flow is decreased from 600m^3/s to 480 m^3/s at 1 hour, from 1 hour to 2 hour, and from 1 hour to 3 hour) and three different lengths of pool(20km, 30km and 40km) is simulated. The result is shown in Figure 7 and Figure 8.

Form the result of simulation, it is concluded that the flow change rate and pool length has a large impact on drawdown. The drawdown is increased along with the increase of flow change rate and pool length. Influence on drawdown by flow change rate is more notable than pool length. The pool length should be confirmed by the simulation of unsteady non-uniform flow in open canal with certain operation control method, but shouldn't be confirmed by the calculation of uniform open canal flow.

Flow change rate has little impact on hydraulic response time using the same control controller in a certain canal. The hydraulic response time is not same on different pool length. The greater the pool length, the longer the response time. The rate of response time increases much slower than the rate of which the pool length increases.

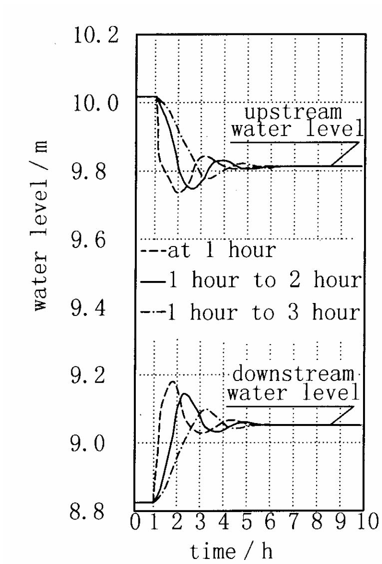


Figure 7. Control with Different Flow Change Rate

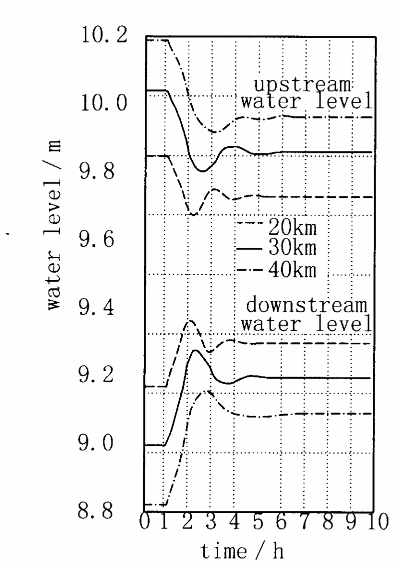


Figure 8. Control with Different Pool Lengths

CONCLUSIONS

In this study, the relationship of operation stability and automatic control methods of open canal is studied by means of numerical simulation of unsteady flow in open canal with different control methods. Form the simulation, the following conclusions can be obtained.

Control model basing on modern control theory and traditional control theory can both be used to the automatic control of canal, but each controller has its own characteristics from others. So chosen of operation control method is very important for a certain canal.

The hydraulic response of the constant volume method of operation is better than constant downstream depth in a certain centralized control canal. So constant volume method of operation is prior chosen on the conditions that the method can be used.

The flow change rate and pool length has a large impact on drawdown. The drawdown is increased along with the increase of flow change rate and pool length. Influence on drawdown by flow change rate is more notable than pool length. Thus, in order to reach an acceptable drawdown rates, a appropriate flow change rate should be chosen instead of shortening the pool length. From the simulation, the pool length of more than 30km can be able to satisfy the acceptable drawdown rates of 0.2m/h of the canal of middle route of China's South-to-North Water Diversion Project when proper flow change rate is chosen.

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