CAD method for analysis and controller design of irrigation canals

L. Skertchly, J.P. Miles

UMIST, Department of Mathematics, Sackville St., PO Box 88, Manchester M60 1QD, UK

Abstract

This paper describes a CAD method which consists of three stages: model formulation, controller design, and system simulation. In the first stage the parameters for a simplified model of the dynamic response of the downstream water depth in a canal reach when an excitation is applied at the upstream end are obtained. Here, each reach is dealt with as a single system. The resultant model response can be compared to the one obtained by numerical simulation. The second stage concerns the selection of control parameters for the design of a controller with a prescribed algorithm. The input signal is the inflow to the reach and the output the water depth at the downstream end of the reach. In the third stage, the resultant control algorithm, for the multi-reach system, can be simulated using the Preissmann discretization scheme for the Saint-Venant equations applied to the canal coupled to the controller. An example is discussed, in which the techniques are applied using data from a real irrigation canal.

1 Introduction

State-of-the-art technology in irrigation has recently attempted to incorporate control techniques in the pursuit of better water application efficiencies. Success would result in better water resources employment, and reduced labour costs.

Recent papers have addressed the problem, whose main difficulties lie in constructing a model to represent the dynamic process of water flow in the canal, and a control algorithm capable of driving the canal from a perturbed
steady state, caused by gate closing or opening, to a new equilibrium steady state.

As pointed out by Balogun et al.\textsuperscript{1}, one of the main reasons for the lack of application of automatic devices in irrigation systems is the unavailability of effective procedures for the analysis and design of automatic feedback control for canals. On the one hand the dynamic processes in canals are not well understood, in regard to their automatic control, and on the other hand the time delays involved in water flows lead to further complexities.

The dynamics of irrigation canals is often described as a succession of steady states. In the transition from one steady state to another, unsteady flow occurs. The problem of controlling an irrigation canal can be stated as how to operate the gates in order to make these transitions as fast as possible and with the least perturbation to the levels and discharges along the reach.

This paper introduces a procedure to design automatic feedback controllers for irrigation canals. A computer model based on the Saint-Venant equations, which describe the water flow in open channels, is used in the three stages of the design procedure. First, a simplified model for each reach of the canal under study is obtained, using numerical simulation. In the second stage, appropriate control parameters are obtained using the simulation model with a controller defined in a subroutine. Finally, the operation of the entire canal can be simulated.

2 Canal Modelling Stage

A means of predicting the effect of input, as inflow to the reach, on the output, as downstream water depth, is needed, taking due account of the time delays mentioned above. The complete set of Saint-Venant equations is difficult to use to this effect, because of the amount of data needed, the availability of information and the time required to process it. Instead, a simplified model can be used, which can use the information obtained from the canal, and is fast enough to provide the accurate responses needed in the decision-taking process.

Various approaches can be taken in the formulation of a simplified model. Balogun et al.\textsuperscript{1}, apply optimal control to the linearized unsteady flow equations representing the system. Zimbelman and Bedworth\textsuperscript{2}, use time-series to predict the system status and hydraulic engineering knowledge to determine control structures behaviour. Gómez et al.\textsuperscript{3}, use a Muskingum model for which the input is the inflow rate and the output the downstream discharge.

In irrigation canals measurements of the water depth at both ends of a reach and check gates openings are usually available. This information allows the calculation of inflow and outflow rates. Based on this fact the usefulness
of a model relating inflow rate and downstream water depth is apparent.

For a single reach, the rate at which the water accumulates, dS/dt, is equal to the difference between the inflow Q_i and outflow Q_o. The storage S, the amount of water in the reach at any time, can be expressed as rAy, where r is a parameter, assumed constant here, which accounts for the difference between the downstream depth and the average depth in the reach, A the area of the free surface of the water and y the downstream depth. Thus

\[ \frac{dS}{dt} = \frac{d}{dt} (rAy) = Q_i - Q_o \]  

(1)

Supposing that the flow rate through the downstream gate can be considered as approximately proportional to the downstream depth, and the inflow proportional to the gate opening, we have

\[ Q_o = \frac{y}{R}; \quad Q_i = g_g \alpha \]  

(2)

where R is a proportionality constant which incorporates the appropriate discharge coefficient and the width of the gate, \( \alpha \) is the gate opening and \( g_g \) is the gate gain, which takes account of the gate discharge coefficient and the appropriate discharge law.

Substitution of eqns (2) into (1) then gives the following differential equation

\[ (rAR) \frac{dy}{dt} + y = (Rg_g) \alpha = Rq \]  

(3)

where \( q \) is the inflow rate. Finally, introducing the new variables \( T = rAR \), the process time constant, and \( G = R \), the process gain, the following differential equation is obtained:

\[ T \frac{dy}{dt} + y = Gq \]  

(4)

If \( q \) is a step function, eqn (4) has the following solution

\[ y(t) = y(0) \exp\left(-t/T\right) + G[1 - \exp\left(-t/T\right)]Q \]  

(5)

which gives the response of \( y \) to a step of size \( Q \) in the inflow at time zero. If \( y(0) = 0 \), then \( y(T) = 0.632GQ \), i.e. \( y \) reaches 63% of its final value at \( t = T \) after the change in inflow \( q \). This justifies the names gain and time constant given to \( G \) and \( T \) respectively.

For short, narrow, and smooth canals, eqn (5) could describe the response of \( y \) to \( Q \), but for long, rough, and wide canals the effect on \( y \) will take some time before it can be observed. The corresponding solution of the differential
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equation is

\[ y(t) = y(0) \exp\left(-\frac{t}{T}\right) + G \left\{ 1 - \exp\left(\frac{-(t-D)}{T}\right) \right\} Q u(t-D) \] (6)

where D is the "dead time" and \( u(t) \) is the unit step function which equals zero whenever its time argument is negative and equals unity otherwise. In discrete form the last equation can be written as

\[ Y_i = Y_{i-1} \exp\left(-\frac{h}{T}\right) + G \left[ 1 - \exp\left(\frac{-h}{T}\right) \right] Q_{i-1-n} \] (7)

where h is the length of the time interval and D is supposed to be a multiple of h.

Figure 1. Model representation of system step response.

During the first stage of the procedure, a simplified model as described above is formulated for every single canal reach. In all stages the input data comprise the average canal reach slope, bed width, side slopes, Manning’s roughness coefficient, reach length, and initial water depth and flow rate at every cross section of the discretization. The results from this stage are summarised in a graph of water depth versus time as in figure 1.

The size of the step must be given by the user, for example as a fraction of the initial flow rate; the criterion for calculation ending is prescribed as a difference between inflow and outflow, within a given accuracy.
3 Control parameter calculation stage

The aim of this stage is to obtain suitable values for the controller parameters. To this end a numerical model of the canal is coupled to a controller, formulated in a subroutine, whose structure is fixed and is explained below. Input data are the basic reach data used in the last stage and the model parameters, the values of the controller parameters (which are initially guessed), a dead band value, and minimum inflow increment.

In this stage, the reach under study is considered to have only an upstream and a downstream connected reach. The reason for this is to avoid time waste when very long or complicated networks are studied.

Starting with the guessed values for the PID controller parameters, the user can increase or decrease those values, assess the effects of so doing, and choose the most appropriate ones.

The control algorithm uses a Smith predictor, i.e. a reference model gives an estimate of the downstream water depth. First, the model is used in calculating the required increment in inflow rate to make up the observed downstream water depth variation. Noting that the disturbance will not have reached its greatest magnitude when it is first detected, the reference water depth is set to twice the actual reference value minus the observed water depth. In so doing, the controller will calculate a compensation which will account for the likely departure to take place immediately afterwards. As the change in input is taking effect, the reference thus calculated will approach the actual reference set point. This makes the controller fast and accurate.

On top of this first compensation, extra control action is applied. Here, an error is defined as the difference between the registered depth and the required depth, \( y_r - y' \), where \( y_r \) is the required depth and \( y' \) is the output from the process model, involving no dead time, i.e. \( y' \) is used instead of the value of \( y \) registered at the downstream end of the canal. The error thus obtained is used in the calculation of proportional, integral, and derivative (PID) control actions.

A typical performance of the control algorithm shows three features: after the disturbance is detected, a control action follows which drives the water depth near its set point, then control action in the reverse direction is carried out until the output signal reaches the set point.

4 Simulation stage

Once the system has been modelled reach by reach and the control parameters for every reach under study have been obtained and tested, the whole system
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can be simulated. The aim of this stage is to simulate globally different scenarios of the system, its perturbations and their control. This simulation will prove very convenient for demonstration purposes, because it can be carried out interactively.

The input data are the same as in the previous stages, except that all the system reaches can be incorporated, and the system behaviour observed as a whole. The output from the system can be seen (and plotted) graphically or analyzed using the resulting ASCI files.

5 Application example

The algorithm presented in this paper was developed for the Main Canal Alto in the Mexican Irrigation System Río Yaqui. Canal Alto is 105 km long, and was constructed to convey and distribute around 1,100 million m³ a year, with a maximum flow rate of 110 m³/s. The first part of the canal is concrete lined, has two regulation reservoirs, three tunnels, four siphons, and eight check structures. The average cross-section is 8.1 m bed width, side slopes 1:1.25, longitudinal slope 20 cm per km average. From check structure K 42 + 000, the canal is earth excavated. It has variable cross-sections: bed 18 to 20 m wide, side slopes of 1:1.5, water depths of 3.6 m, and average longitudinal slope is 13 cm per kilometre. In this section most of the lateral canals are connected, there are ten check structures for its operation.

As a demonstration of the controller performance an example follows. A perturbation is produced in the reach between check structures K 47 + 520 and K 52 + 876, the sixth canal reach. This canal pool has a lateral reservoir with a considerable area, also its length is one of the greatest among the canal reaches. The model used as reference has a large time constant and the gain is low as the free surface of the water is large. Plots of water depths (5.0 cm around their set points [S.P.]) at the downstream end of the reach considered and of the upstream and downstream adjacent reaches, are shown together with the inflow to the reach under consideration on figure 2.

Initially the inflow to the reach is 24.00 m³/s, the outlet is demanding 4.2 m³/s, and the remaining 19.8 m³/s are discharged into the next reach. The disturbance is produced as the outlet is opened to increase the demand 2.0 m³/s, to 6.2 m³/s, the increase representing 8.3 % of the inflow. About an hour later, the change in demand is detected, when the downstream water depth drops to 4.27 m. From that moment the inflow is increased in steps of 0.100 m³/s. The control action is applied for about 10 hours, until the depth is within 0.005 m of the set point. However, the required inflow rate is achieved less than an hour after the disturbance is detected. This is due to the large free surface of the water, which means that for any small change in water depth a large volume of water must be added/withdrawn from the reach storage.
6 Conclusions

Similar tests to the one described here were carried out on each of the reaches of the canal, Sketchly and Miles. Results show that the controller restores the set point downstream water depth using only information on actual water levels and gate openings. In all the cases considered the controller prove to be accurate, fast, and stable, despite the variable characteristics of the canal reaches involved.

The proposed method of control for a multi-reach canal achieves the objective of maintaining the water depths close to a set point. The control actions are carried out in a relatively short time, because they are applied simultaneously at the reaches upstream from the reach under control.

The method has proved to be equally effective whether the reaches are short or long, wide or narrow, or have steep or mild slopes. The reference model can be easily formulated as only three parameters are involved. These can be obtained using either or both on site measurements or a numerical model based on the Saint-Venant equations.

The advantages of the algorithm can be compared to those of the downstream demand-oriented systems in that both can meet the requirements of flexibility in respect of rate, time, and duration of demand. The only
limitations which the proposed method exhibits are caused by the inherent characteristics of the physical phenomena of open channel flow.

The procedure described here has proved effective in the application of Canal Alto controller design. The CAD presented gives the user an insight into the structure of the algorithm, as the effect of varying controller parameters can be observed in the control stage. The behaviour of the resultant controller can be assessed in the simulation stage when all the canal reaches and their features can be incorporated in a single global system.

7 References


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