AUTOMATIC UPSTREAM CONTROL SYSTEM FOR CANALS

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ABSTRACT

Automatic upstream control is applicable to canals designed as supply-oriented conveyance systems. A study was made to develop an automatic upstream control system utilizing the P+PR (proportional plus proportional reset) mode of control for the Bypass Drain check gates of the Yuma Desalting Plant. Mathematical model simulation studies show the P+PR controller can automatically transfer all degrees of flow change from upstream to downstream and return the water levels (upstream of canal check structures) back to desired target levels within a reasonable period of time. Included in the study were the development of a digital filter for microprocessor units and a technique for reducing "saw-tooth" gate control responses during steady-state flow conditions.

INTRODUCTION

The Bypass Drain is being designed to convey reject flow (brine) from the Yuma Desalting Plant and excess Wellton-Mohawk drainage water to the United States-Mexico International Boundary (fig. 1) as part of the Colorado River Basin Salinity Control Project, Title I Division. A description and physical properties of the Bypass Drain are summarized in appendix I. Upstream control is the most logical concept to transfer the reject flow and excess drainage water downstream. The results of the study to develop the control algorithm for automatic upstream control are presented in this paper.

An analysis was made of the proportional plus proportional reset, labeled the P+PR, mode of control as the basic method of an automatic upstream control system. Included in the P+PR study was the development of a digital filter and a technique to reduce "sawtooth" gate response characteristics during steady-state flow conditions. The filter element is required to eliminate unnecessary gate responses to wind-wave action and local disturbances. The reduction of "sawtooth" gate responses reduces the wear and tear on the gate hoist mechanism.

The background leading to the analysis of the P+PR mode of control application to automatic upstream control is discussed. A description of the automatic upstream control and the general theory including control parameter selection of the P+PR control mode as it applies to the automatic upstream control of canal check gates is given. Included is the development of the digital filter and the technique used to reduce the "sawtooth" gate steady-state response. Finally the advantages, disadvantages, and summary and conclusions are offered. This paper does not include technical descriptions of the equipment necessary to implement the P+PR automatic upstream control system.

BACKGROUND

Development of automatic upstream control systems has previously been accomplished largely through field trial and error experimentation. The set-operate-time/set-rest-time method known as "Little Man" is an example of a simple control system designed to maintain constant water surface elevations upstream of check structures and was developed empirically by field operating personnel through field experimentation over several years [1]*. The original design was modified to increase capability and to overcome some of the problems that cause instability [2]. The set-operate-time/variable-rest-time method known as the "Colvin Controller" has been developed

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*Parenthetical [ ] numbers refer to literature cited.

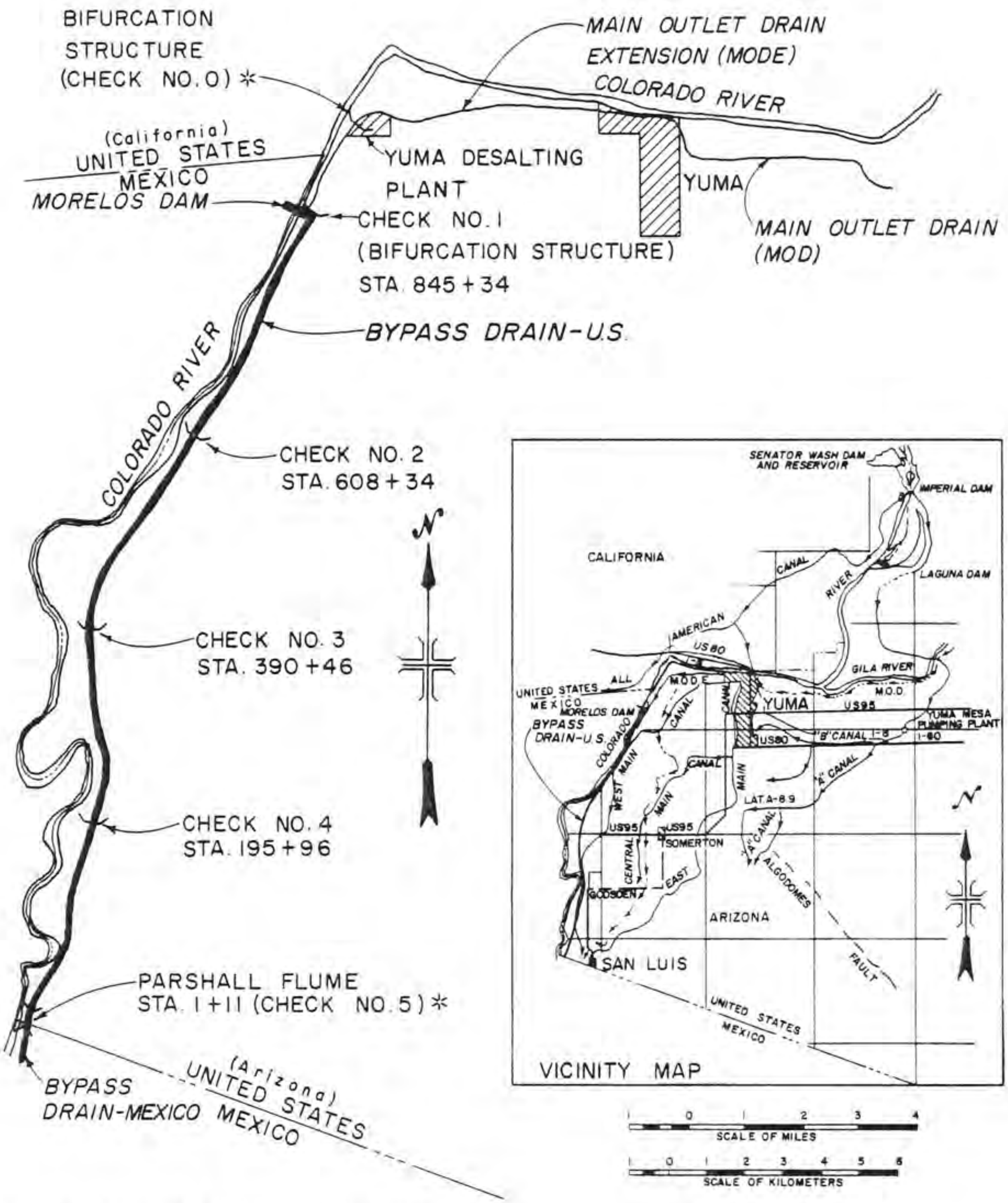
in recent years by field experimentation with minimal mathematical model simulation studies. The HyFLO, and later the EL-FLO plus RESET method of automatic downstream control of canal check gates, used mathematical model studies exclusively to develop the control system [3, 4]. Field tests were then made to verify the theoretical analysis and the mathematical model simulation [4]. The basic mode of EL-FLO plus RESET method control, otherwise called "proportional plus proportional reset," has been applied to the automatic upstream control of canal check gates [7]. The study of an upstream control system for the Bypass Drain presented in this paper is the first extensive effort to develop a suitable and stable automatic upstream control system for canal check gates. Through past experience, enough confidence has been gained in the accuracy of mathematical model simulation that the results of the studies can be applied directly to the prototype installation.

AUTOMATIC UPSTREAM CONTROL CONCEPT

The upstream control concept is "the transfer of upstream inflow changes to points of delivery downstream." Upstream control is applicable to supply-oriented canal systems. Applying the upstream control concept to a main canal system means the source of water, collected from many canalside inlet drains for example, is transfered downstream to selected points of delivery. Automatic upstream control automatically transfers the upstream source of water downstream through intermediate canal check gate structures to the point of delivery without supervisory intervention.

Main canal systems for drainage projects are designed and constructed to collect water from many sources en route and deliver the water downstream to a holding reservoir, desalting plant, or to the ocean. The drain system capacity begins small and ends with a maximum design capacity as drainage inflows from project lands increase en route.

The operation of a main canal for a drainage collection system requires all inflows to be delivered downstream. As the inflows vary, the intermediate check gate structures must be regulated to prevent flooding or serious water level drawdowns within the canal prism. Manual operation involves the "ditchrider" following the wave, by which the change of canalside inflow is propagated downstream, making adjustments in the canal check gates when the front of the wave arrives. Automatic upstream control increases the canal check gate opening, without supervision, when the front of a positives wave arrives, an indication that canal inflows have increased. The increase in the controlled gate opening immediately downstream, increases the flow into the downstream canal reach. Likewise, a decrease in the water surface elevation upstream decreases the flow downstream. Changes in canal flow arriving at a



* Note: Check No. 0 and check No. 5 are used in this report as labels for the M.O.D.E. Bifurcation structure and the Bypass Drain Parshall Flume.

Figure 1. - Bypass drain location map.

check gate from upstream are, therefore, automatically transferred downstream.

THE P+PR CONTROL

The P+PR (proportional plus proportional reset) mode of control has been applied to the automatic upstream control concept. The elements of the P+PR automatic upstream control system are shown in the block diagram, figure 2. The first element is the sensor that measures the water surface in the stilling well located immediately upstream of the controlled gate. The output signal, YWELL, of the stilling well water level sensor is modified by the filter element to eliminate unnecessary gate movements that would be caused by wind-wave action or local disturbances of short durations. The requirements for the filter element are described in subsequent paragraphs. The output signal, YF, of the filter element is the input to the proportional, P-controller, and to the proportional reset, PR-controller. The P-controller solves the equation:

$$GP = K1 * (YF - YT) \qquad (1)$$

where:

GP is the desired P-controller gate opening
K1 is the proportional gain constant
YT is the selected target water level
YF is the canal water level modified by the filter element

The PR-controller solves the equation:

$$GR = K2 * \int_0^t [(YF - YT) \pm RDB]dt \qquad (2)$$

where:

GR is the desired PR-controller gate opening
K2 is the proportional reset gain constant, per second
t is real time, seconds
dt is the discrete time interval, seconds
±RDB is the required deadband for the PR-controller

The amount of "offset", (YF-YT), when multiplied by the P-controller gain, K1, results in a positioning of the controlled gate (immediately downstream) to control the flow into the downstream canal reach. The residual water level "offset" characteristics of the P-controller are gradually eliminated by the PR-controller as time progresses. The PR-controller integrates or sums the area of the "offset" with respect to time. The accumulated area is multiplied by the PR-controller gain, K2, to obtain an additional positioning of the controlled gate.

The P-controller provides the primary control response immediately after a flow change from upstream arrives at the water level sensor. As a new steady-state flow condition develops at the target depth, YT, the PR-controller provides the primary control response. Typical response of the P+PR automatic upstream control to a sudden increase of canal flow upstream is shown in figure 3. The PR-controller does not sum the area with the PR-controller deadband, RDB, and it is turned "on" when the absolute value of the "offset" (YF-YT) is greater than or equal to RDB (fig. 3b).

The output signals, GP and GR, (fig. 2) of the P- and PR-controllers are input signals to the comparator unit. The comparator unit sums algebraically the input signals, GP and GR, to obtain the total gate opening, GD, as follows:

$$GD = GP + GR \tag{3}$$

The total desired gate opening is then compared to the actual gate position, GA, to obtain the error signal, $\pm\Delta G$, as follows:

$$\pm\Delta G = GD - GA \tag{4}$$

The value of actual gate position, GA, is measured by a sensor usually driven by the gate hoist shaft. If the error signal, $\pm\Delta G$, is greater than the referenced gate movement deadband, GDB (fig. 3c), the comparator unit (fig. 2) will energize the raise or lower relay of the actuator element. The actuator then energizes the gate motor to raise or lower the gate depending on the polarity of the error signal, $\pm\Delta G$. The gate will raise or lower until the error signal, $\pm\Delta G$, is zero, at which time gate motion stops. The gate movement referenced input deadband, GDB, is necessary because of the very fast rate of gate movement characteristic relative to the computed desired gate opening, GD.

A relatively simple analysis can be made to determine the approximate values of the P+PR control parameters, K1 and K2 in equations (1) and (2) above. The basic criterion for the P+PR automatic upstream control system is to maintain continuity at the controlled gate (fig. 2). The change of flow, ΔQ_{in} arriving from upstream should be equal to the flow, ΔQ_{out}, transfered downstream through the check gate:

$$\Delta Q_{in} = \Delta Q_{out} \tag{5}$$

ΔQ_{in} can be expressed in terms of an elementary wave traveling downstream in a trapezoidal channel as follows:

$$\Delta Q_{in} = \Delta Y * T\ (V + C) \tag{6}$$

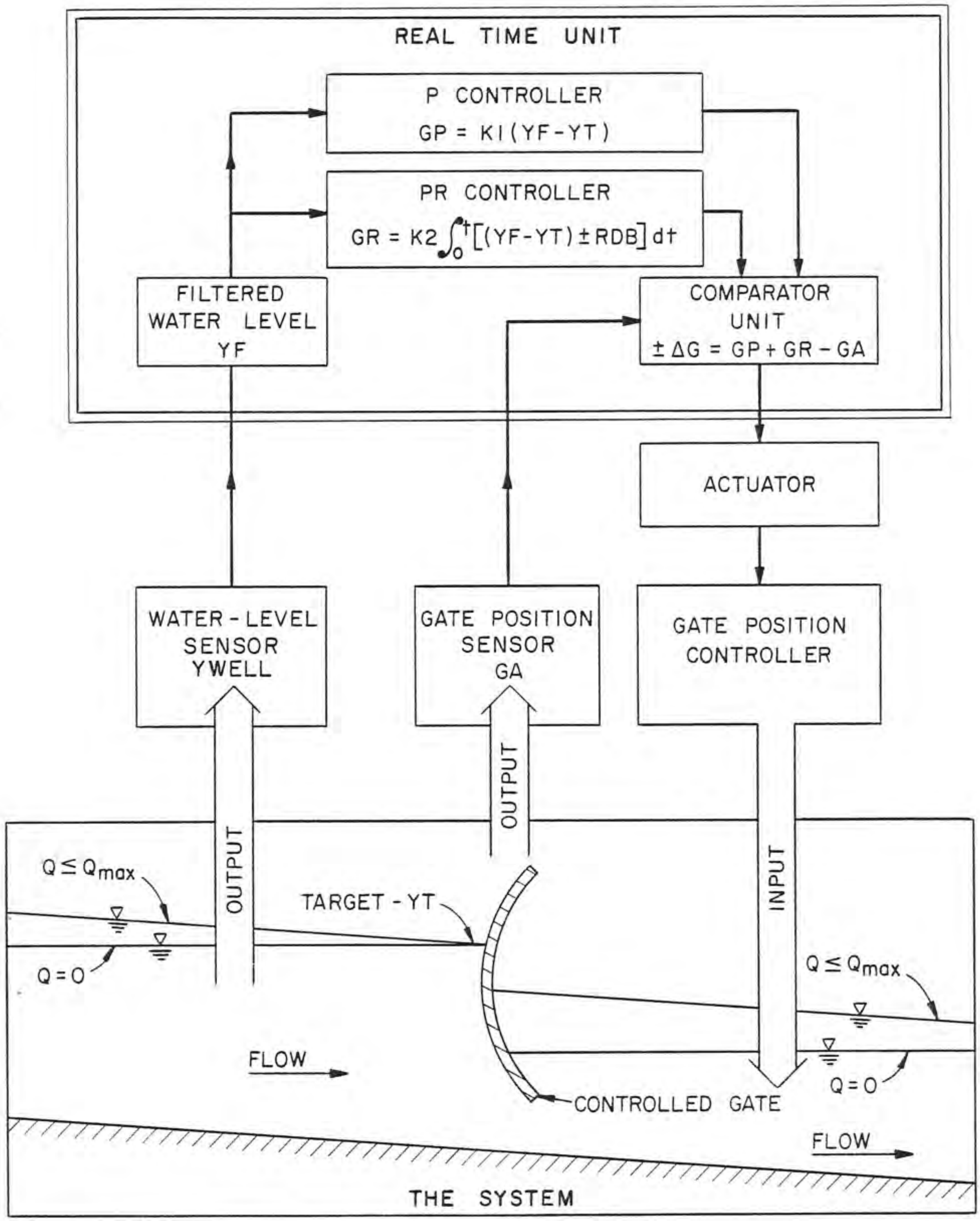


Figure 2. - Proportional plus Proportional Reset (P+PR) automatic upstream control system block diagram.

where:

ΔY is the change in the upstream depth
T is the top width of the water surface
V is the upstream channel velocity
C is the wave celerity equal to $\sqrt{g \frac{A}{T}}$ where A equals the cross section area of the total flow

In simplified terms, ΔQ_{out} can be expressed as flow through the controlled check gate as follows:

$$\Delta Q_{out} = \Delta G * B * C_d \sqrt{2g(\Delta H)} \qquad (7)$$

where:

ΔG is the change in the check gate opening
B is the gate width
C_d is the coefficient of discharge
H is the head differential across the check gate

The ratio of $\Delta Q_{out}/\Delta Q_{in}$ must be unity if stability is to be maintained and would be expressed as follows:

$$\frac{\Delta Q_{out}}{\Delta Q_{in}} = \frac{\Delta G\ B * Cd\sqrt{2g\Delta H}}{\Delta Y\ T\ (V + C)} = 1 \qquad (8)$$

By transposing, the ratio of $\Delta G/\Delta Y$ can be found as:

$$\frac{\Delta G}{\Delta Y} = \frac{T\ (V + C)}{B * C_d\sqrt{2g\Delta H}} \qquad (9)$$

The ratio of $\Delta G/\Delta Y$, by definition, is the GAIN for the controller and is the first control parameter, K1, for the P-controller. The GAIN, K1, can be found as follows:

$$K1 = \frac{T\ (V + C)}{B * C_d\sqrt{2g\Delta H}} \qquad (10)$$

The latter equation shows that the GAIN of the controller is dependent upon the characteristics of the upstream channel and the width and flow (submerged or free-flow) through the controlling check gate.

The Bypass Drain check No. 1 is used as an example to estimate the P-controller gain, K1, solving equation (10) above. The steady-state flow condition used is 0.28 m^3/s (10 ft^3/s). The low flow

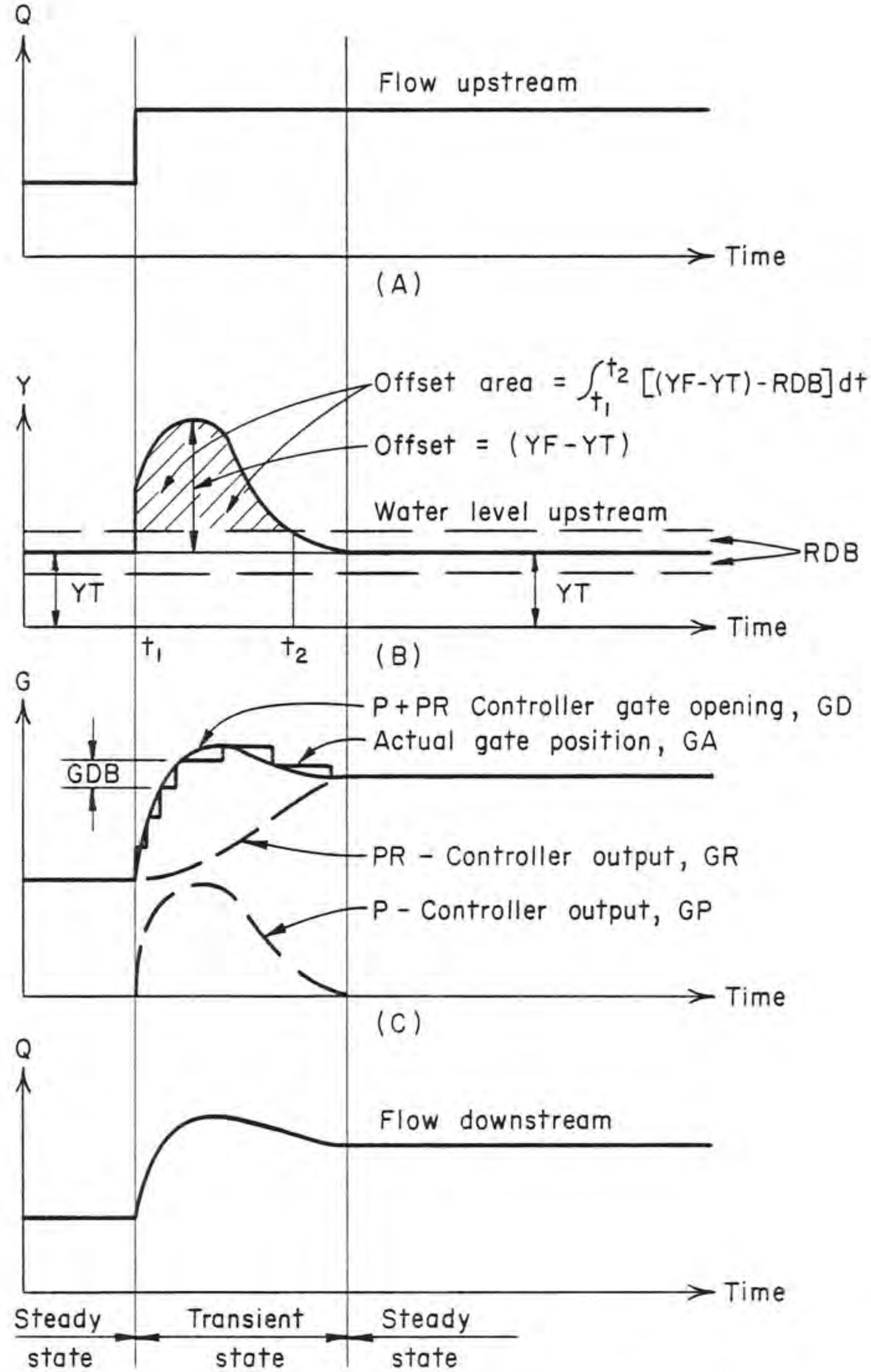


Figure 3. - Typical response of the P+PR automatic upstream control to a sudden increase of upstream canal flow.

condition was selected because the head differential, ΔH, across the check gate is near its maximum value resulting in a minimum gain, K1, calculation. The minimum gain, K1, becomes the maximum selected gain for the P-controller in order to regulate flow changes with stability, at the low flow conditions. At the 0.28 m^3/s (10 ft^3/s) flow, the head differential, ΔH, across the Bypass Drain check stability, at the low flow conditions. At the 0.28 m^3/s (10 ft^3/s) flow, the head differential, ΔH, across the Bypass Drain check No. 1 is 0.63 m (2.08 ft) and the coefficient of discharge, C_d is 0.80. Using the physical properties of the Bypass Drain, appendix I, the calculated minimum gain, K1, of equation (10) is 3.1 m/m (3.1 ft/ft) and would be the maximum gain of the P-controller. However, the P-controller is used in parallel with the PR-Controller, (fig. 2). When the two controllers are operated in parallel, the P-controller gain needs to be reduced by a factor of 3 in order to prevent the continuity, equation (5), or the ratio of ΔQ_{out} to ΔQ_{in} from exceeding unity by a large amount. The factor of 3 was developed largely through experience. Further discussion of the combined P- and PR-controller is provided is subsequent paragraphs.

Referring to figure 3, the primary function of the PR-controller is to eliminate the residual water level "offset" of the P-controller and thereby restore the canal capability for maximum flow and designed canalside inflow capacities. Observe that the P-controller provides the primary control response immediately after the flow change upstream has taken place. As a new steady-state flow condition develops at target water depth, YT, the P-controller influence approaches zero and the PR-controller provides the primary control response.

The selection of the PR-controller gain, K2, is somewhat arbitrary. If the gain, K2, were too large, fast elimination of the residual "offset" may cause undesirable effects by amplifying the change of flow into the downstream reach. However, the gain, K2, cannot be too small because a too long period of adjustment may be required to eliminate the residual offset causing undesirable water levels for long periods of time. Therefore, the selection of the PR-controller gain, K2, is based primarily on how fast the water levels should recover back to the target level desired at steady-state flow conditions. A practical recovery rate for the P+PR automatic upstream control system is a 90 percent recovery of the residual offset after about 100 minutes of time from the initial disturbance, t_1 to t_2, figure 3(B), for a typical change of flow from upstream.

Using the 90 percent, 100-minute recovery criteria, an estimate of the PR-controller gain, K2, can be made:

where:

$$K2 = \frac{\Delta GR}{0.9 * \Delta Yave * t} \qquad (11)$$

where:

ΔGR is The change of gate opening from one steady-state to the next
$\Delta Yave$ is The average "offset" during the period of time, t_1 to t_2 fig 3 (B)
t is the desired recovery period of 100 minutes

The denominator of equation (11) above is essentially an estimated "offset area", figure 3 (B).

If an average ΔY is assumed to be 0.01 m (0.03 ft) for the 100-minute recovery period, the GR can be found using equation (9) and the same flow conditions used previously to calculate the P-controller gain, K1. The PR-controller gain, K2, using equation (11) can then be calculated and found to be a value of 0.00055 per second. The selected value actually used in the PR-controller for the P+PR Bypass Drain check gate automatic upstream control was 0.00058 per second.

The assumed ΔY of 0.01 m (0.03 ft) was derived from equation (6) based on a typical change of flow, ΔQ_{in} expected to occur from upstream of 0.3 m^3/s (11 ft^3/s) 90 percent of the time.

When the P-controller is combined with the PR-controller and the two are operated in parallel, a further check on the selected gains, K1 and K2, should be made to insure the continuity equation (5) is satisfied. The check can be made using the assumed ΔY of 0.01 m (0.03 ft) which is the average change of depth during the period t_1 to t_2, figure 3(B). It can be assumed the peak ΔY will be twice the average or 0.02 m (0.06 ft) and will occur at 30 minutes after the initial distance of time t_1. With this information, equations (1) and (2) can be solved for ΔGP and ΔGR. Adding the two outputs, ΔGP and ΔGR, together to get the total ΔG, the flow through the gate, ΔQ_{out} can be found from equation (7). The flow change from upstream, ΔQ_{in}, can be found from equation (6). The ratio of ΔQ_{out} to ΔQ_{in} should be less than or equal to unity. Using a P-controller gain, K1, of 1.0 m/m (1.0 ft/ft) and the PR-controller gain, K2 of 0.00058/s, the ratio calculation is summarized:

$$\frac{\Delta Q_{out}}{\Delta Q_{in}} = \frac{(\Delta GP + \Delta GR) * B * C_d * \sqrt{2g\Delta H}}{\Delta Yave * T\ (V + C)} \leq 1 \qquad (12)$$

where:

ΔGP is K1 * ΔY peak = 1.0 * 0.02 m = 0.02 m (0.06 ft)
ΔGR is K2 * ΔYave* Δt = 0.00058/s * .01 m * 1800 s = 0.1 m (0.03 ft)
B is 3.66 m (12 ft)
Cd is 0.80
ΔH is 0.63 m (2.08 ft)
T is 8.97 m (29.43 ft)
V is 0.025 m/s (0.083 ft/s)
C is 3.50 m/s (11.48 ft/s)

and therefore:

$$\frac{\Delta Q_{out}}{\Delta Q_{in}} = \frac{0.28\ m^3/s\ (10.15\ ft/s)}{0.29\ m^3/s\ (10.20\ ft/s)} \leq 1 \qquad (13)$$

The above check on continuity also demonstrates the need to reduce the P-controller gain, K1, calculated in equation (10) by a factor of three when the P-controller is combined or operates in parallel with the PR-controller.

It should be stressed that the above analysis can be used to determine the approximate values of the P+PR controller gains, K1 and K2. The approximate method should provide a good idea as to the magnitude of the controller gains for any particular installation of the P+PR automatic upstream control system. Greater accuracy can be achieved through complete mathematical modeling of the canal and control system and should be accomplished before selecting final values.

The PR-controller requires a deadband, ±RDB, figure 3(B) and should be selected wide enough to provide good stability characteristics at the steady-state flow conditions. The P+PR controller deadband, ±RDB, is selected based on the performance of the P-controller at steady-state flow conditions. The P-controller will operate the gate according to equation (1). Using a gate deadband, ±GDB, of 0.03 m (0.1 ft) and a gain, K1 of 1 m/m (1 ft/ft), the "offset", (YT-YF), would be 0.03 m (0.1 ft). The "offset" of 0.03 m (0.1 ft) would develop when there is a minor mismatch of flow, i.e., ΔQ_{in} is not equal to ΔQ_{out}. The P-controller will operate the gate to adjust for the mismatch and a "sawtooth" operation (discussed in subsequent paragraphs) will develop. The PR-controller should not be allowed to operate within the minor mismatch flow range of the P-controller. Amplification of the mismatch could occur and cause an unstable control operation at the steady-state flow condition. Therefore, the PR-controller deadband, ±RDB, should be at least ±0.03 m (+0.1 ft) wide which is the smallest range of control operation of the P-controller. A selected value of 0.024 m (0.08 ft) was actually used for the Bypass Drain P+PR automatic upstream control system.

THE FILTER

The investigative approach used the assumption that the water surface sensor (fig. 2) would be located a very short distance upstream of the controlled gate. Therefore, the dead time of the system, the time required for a transient wave to travel between the water level sensor and the gate, would be very short. A system with a very short dead time would not need a time lag compensator to provide control stability. However, the stilling well design does not provide sufficient or satisfactory dampening characteristics. Waves of high magnitudes and of relatively high frequency caused by the wind or from local disturbances, such as from gate movements, would not be significantly dampened by the stilling well. As a result, frequent gate control responses will occur which are not associated with changes of flow upstream. The unnecessary gate responses caused by wind or local disturbances can be eliminated for this purpose only by including the filter element having a small time constant, TC.

The filter element is a necessary time lag compensator for automatic downstream control systems such as the EL-FLO plus RESET controller [4]. For the EL-FLO plus RESET control system, the filter-time constant, TC, ranges from 100 to 4,000 seconds to provide control stability. Effects of waves of high frequency are filtered out with a time constant of 100 seconds or more and, therefore, are not a problem with automatic downstream control systems.

An electronic filter as used in the EL-FLO plus RESET controller could be used as a filter element in the P+PR automatic upstream control system. Using a time constant, TC, of 100 seconds, high-frequency waves would be damped out. The design of the electronic filter is adequately described in reference [4].

A hydraulic filter could also be used. The hydraulic filter involves a small well with a very small diameter capillary tube inlet placed inside the canalside stilling well. The filtered water surface elevation, YF, in the small well would be measured for the input signals to the P+PR controller. References [5] and [6] adequately describes the hydraulic filter design. However, long-term operation of a hydraulic filter has not proven to be reliable [4].

This paper offers a digital filter that could be used in microprocessors or where logic circuits are available. The digital filter is actually a mathematical simulation of the hydraulic filter, [5] and [6],figure 4, using the finite element method to solve for the new filter water surface elevation, YF.

The energy equation for head loss across the capillary tube, figure 4, with entrance and exit losses neglected, at time t_1 is:

$$YW_{t1} - YF_{t1} = \frac{fL}{2gd_c} * \left(\frac{Q_{tube}}{\frac{d_c^2}{4}} \right)^2 \qquad (14)$$

where:

YW_{t1} is the stilling well water level at time t_1
YF_{t1} is the hydraulic filter well water level at time t1
f is the friction factor
L is the length of the capillary tube
d_c is the inside diameter of the capillary tube
Qtube is the laminar flow through the capillary tube

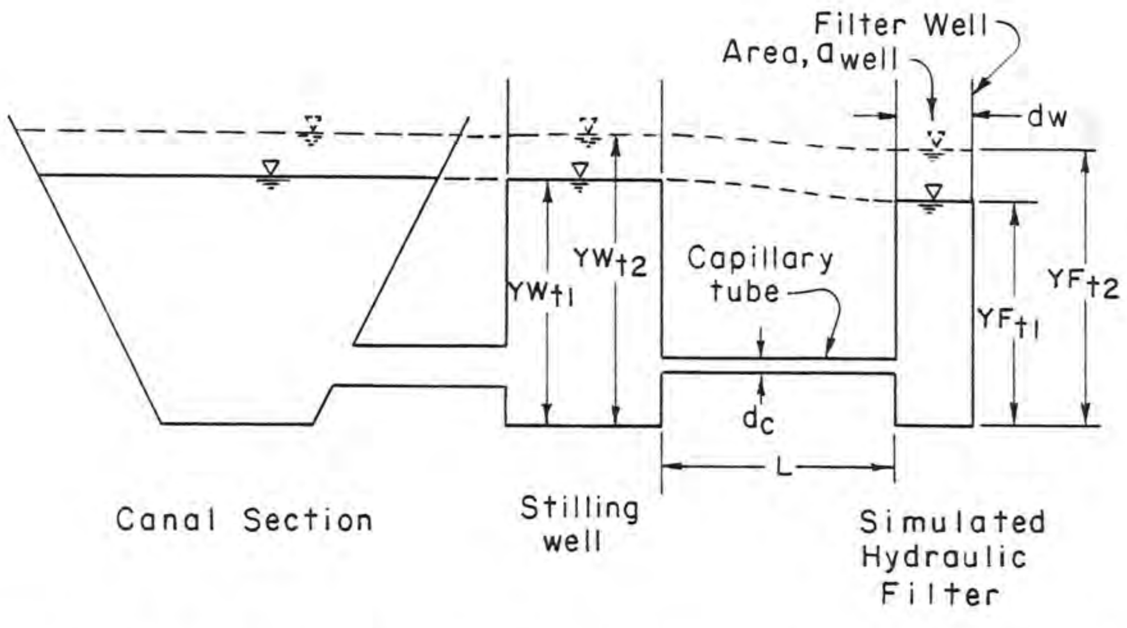


FIGURE 4-SCHEMATIC OF THE CANAL, STILLING WELL, AND THE SIMULATED HYDRAULIC FILTER CROSS-SECTION

The capillary tube is designed for linear damping and, therefore, the flow through the tube is laminar. The friction factor, f, is thus related to the Renolds Number, N_R by:

$$f = \frac{64}{N_R} \qquad (15)$$

where:

$$N_R = \frac{Q_{tube}}{\frac{\pi d_c^{2}}{4}} * \frac{dc}{\nu} \qquad (16)$$

is the kinematic viscosity of water.

Equations (14), (15), and (16) can be combined to give the flow, Q_{tube}, through the capillary filter at time t_1:

$$Q_{tube,\ t1} = \frac{YW_{t1} - YF_{t1}}{k} \qquad (17)$$

where: $k = \frac{128\nu * L}{\pi g d_c^{4}}$

and at time t2: $$Q_{tube},\ t2 = \frac{YW_{t2} - YF_{t2}}{k} \qquad (18)$$

The equation of continuity for flow in the hydraulic filter well and capillary tube is:

$$Q_{well} = \frac{A_{well}\ (YF_{t2} - YF_{t1})}{DT} = \frac{Q_{tube,\ t1} + Q_{tube,\ t2}}{2} \qquad (19)$$

where:

Q_{well} is the average flow in the filter well
A_{well} is the filter well water surface area
$(YF_{t2} - YF_{t1})$ is the change in the water level in the filter well
DT is the change in time corresponding to the filter well change in water level

The sum of equations (17) and (18) combined with equation (19) gives the solution for the new filter water surface, YF_{t2}, as follows:

$$YF_{t2} = \frac{CIDT\ (YW_{t1} + YW_{t2}) - YF_{t1}\ (CIDT-1)}{(CIDT+1)} \qquad (20)$$

where:

$CIDT = \frac{0.5*DT}{TC}$ is the constant representing the simulated hydraulic filter

DT is the discrete time interval (seconds)

$TC = A_{wells}*k$ is the filter well time constant (seconds)

YW_{t1} is the old measured stilling well water level

YW_{t2} is the new measured stilling well water level

YF_{t1} is the old simulated filter well water level

YF_{t2} is the new simulated filter well water level

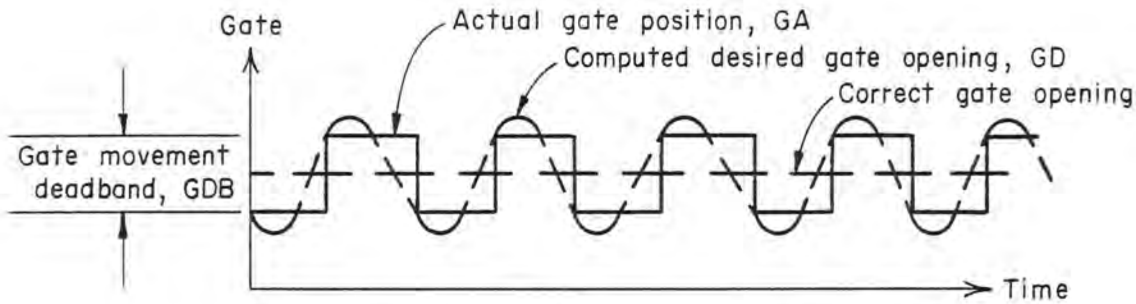
The stilling well level and simulated filter well, YW_{t1} and YF_{t1}, must be replaced with the current values, YW_{t2} and YF_{t2}, respectively, before the real time computation at the next discrete time interval occurs.

The selection of the discrete time interval, DT, is very important. It must be 0.5 second or less in order to define a high-frequency sinusoidal wave with a period of 1 second or less. Therefore, the water surface sensor output, YWELL, is measured and equation (20) is computed at intervals of DT equal to 0.5 second. The time interval, DT, could also be the same dt in equation (2). However, the equation (2) discrete time interval, dt, could be much larger (such as 60 seconds) without affecting the accuracy of the PR-controller output, GR.

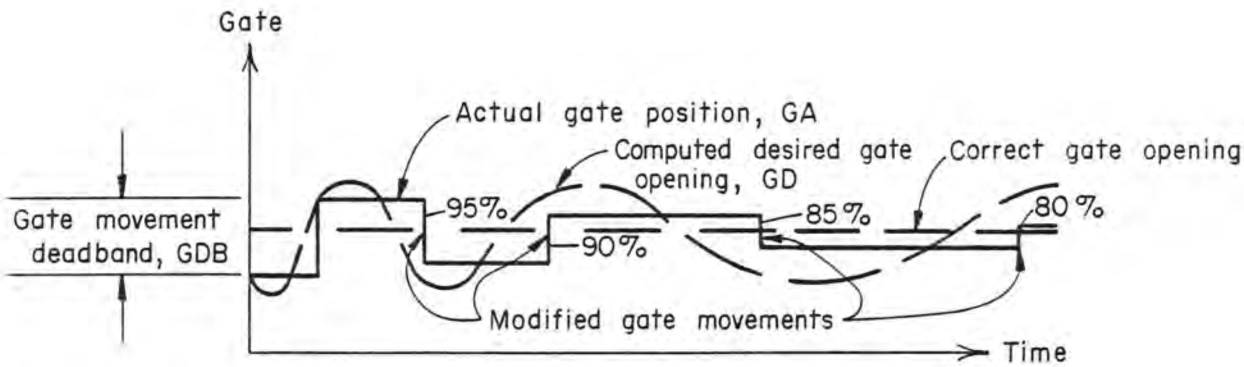
Gate Movement Deadband Modification

A gate movement deadband, GDB, is necessary because of the very fast rate of gate movement characteristics relative to the computed desired gate opening, GD equation (3). For example, the bypass drain gate hoist moves the gate at a rate of 0.43 m/min (1.42 ft/min) as compared to a typical computed gate opening, GD, rate of 0.006 m/min (0.02 ft/min). Therefore, the gate movement has to be stepped into position. The stepping or "jogging" happens whenever the selected difference or deadband, GDB, occurs between the computed gate opening, GD, and the actual gate opening, GA, as described earlier.

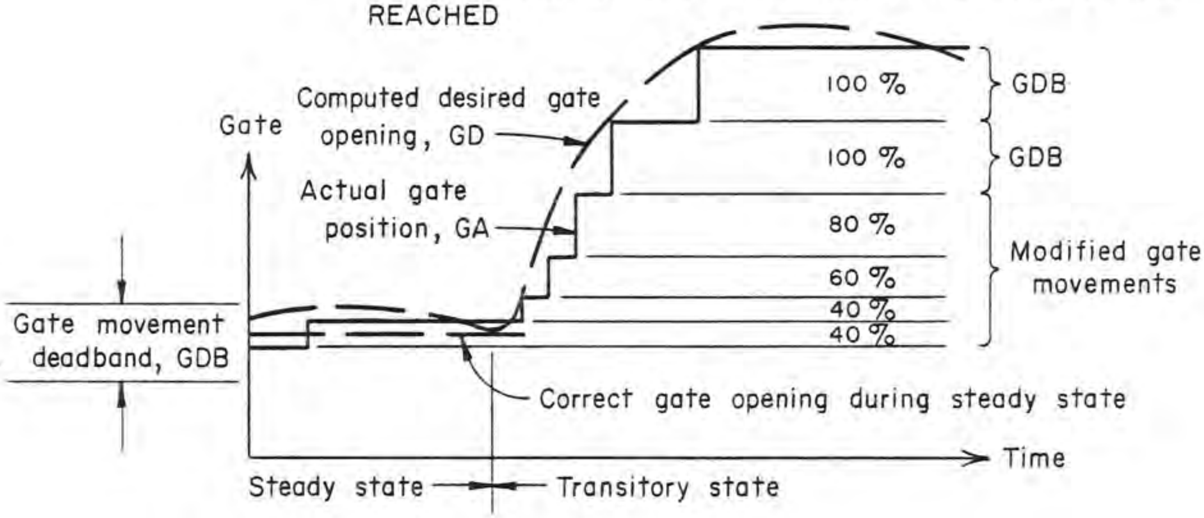
The jogging of the gate into position during the transient state (fig. 3) does not present a problem. However, during the steady state, gate jogging can be frequent, causing many gate movements and the wear and tear on mechanical equipment of the gate hoist increases. Figure 5(A) illustrates a typical gate "sawtooth" operation during a steady-state flow condition. The number of sawtooths can be as many as six to eight per hour. If logic can be programed by using a microprocessor unit or by using logic circuits added to the analog-type controllers, a relatively simple procedure can reduce the number of sawtooth gate operations in a given time period by a factor of 40.



(A) – TYPICAL GATE SAW-TOOTH OPERATION DURING STEADY STATE FLOW CONDITIONS.



(B) – GDB MODIFICATION OF A GATE SAW-TOOTH OPERATION DURING STEADY STATE FLOW CONDITIONS. GATE MOVEMENTS ARE REDUCED BY 5% INTERVALS UNTIL 40% OF GDB IS REACHED



(C) – GDB MODIFICATION OF A GATE SAW-TOOTH OPERATION FROM STEADY TO TRANSITORY STATE FLOW CONDITIONS. (STARTING WITH MINIMUM MODIFIED GATE MOVEMENTS OF 40% OF GDB)

Figure 5. - Gate saw-tooth operation (A) modified, ((b) and corrected (c) by the GDB modification procedure.

The procedure developed in this report is labeled the "GDB modification." The gate movement deadband, GDB, is not actually changed. The gate, however, is not allowed to travel the full distance of the deadband, GDB. If the gate movement direction is opposite to the last gate movement, the gate travel distance is reduced by 5 percent. The 5 percent reduction continues as long as each gate movement is in the opposite direction of the previous gate movement until a minimum value of 40 percent of the deadband, GDB, is reached.

The sawtooth operation is modified [fig. 5(B)] but not completely eliminated by the GDB modification. The GDB modification procedure, however, allows the gate to obtain a position closer to the correct gate opening [fig. 5(A)]. Notice [fig. 5(B)] the value of the gate movement deadband, GDB, remains constant and that for each reverse gate movement the gate is allowed to move 95 percent of GDB, then 90 percent, 85 percent, 80 percent, etc. The minimum value should not be less than 40 percent because of the very short run times (about 2 seconds) involved in operating the gate hoist motors. Shorter run times may damage the motor windings.

It is important that the GDB modification selected as 5 percent not be too large. Larger corrections can cause the gate to undershoot and the next gate movement will be in the same direction.

The GDB value obtained as a result of the modification procedure just described must be "restored" when a change of flow occurs or the canal is now in the transitory state. If the next gate movement is in the same direction as the previous direction, the percent of GDB modification remains the same and the gate moves the same distance as the previous distance. If, however, the gate has moved in the same direction for three consecutive jogs, the gate travel distance is increased by 20 percent. The 20 percent increase continues as long as the gate continues moving in the same direction and until 100 percent of the GDB modification is reached. The "restoration" procedure results in a slower initial response to changes of flow and may cause a slightly larger offset (fig. 3b) before the water surface elevation returns to the target value. The slower response at the beginning of the transitory state, however, was not considered to have significantly affected the desired response of the control system. In figure 5(c) the GDB value starts with a minimum of 40 percent during a steady state, and is restored to 100 percent after three gate movements during the transitory state.

P+PR CONTROL PARAMETER SUMMARY

The control parameters were selected to achieve desirable water level response characteristics, and include the P-controller gain, K1; the PR-controller gain, K2; the filter time constant, TC; the target depth, YT; and the deadbands for gate movement, GDB, and the PR-controller, RDB. The control parameters are dependent on the geometry of the check gate structure and the canal section immediately upstream and downstream. Because the geometry, including the bottom slope and the distance between check gates, is nearly the same; the control parameters are identical for all of the Bypass Drain check gate structures. The dead time of the system (the travel time of a transient wave between the upstream water surface elevation sensor and the controlled gate) is very short. A filter is, therefore, not required as a timelag compensator to maintain control stability. However, a filter with a time constant of 100 seconds is required to eliminate gate control responses that would be caused by high-frequency wind waves or local disturbances as discussed previously. The selected control parameters are summarized (table 1) for the recommended Bypass Drain P+PR automatic upstream control system including maximum discrete time intervals.

Table 1. - Bypass drain P+PR control parameters

No.	Bypass drain check STA m	Sta. (ft)	Target YT m	(ft)
1	258+65.96	(845+34.0)	1.77	(5.81)
2	185+42.20	(608+34.0)	1.85	(6.06)
3	119+01.22	(390+46.0)	1.65	(5.41)
4	59+72.86	(195+96.0)	1.65	(5.41)
5	0+33.83	(1+11)	Free flow 6-m (20-ft) Parshall flume, $Q = 76.25\ H_a^{1.6}$	

Parameters common to all bypass drain checks except number 5:

P-gain (K1) = 1.0
PR-gain per second K2 = 0.00058
Filter (TC) = 100 seconds
Discrete time intervals:
  P+PR DT (max) = 60 seconds
  Filter DT (max) = 0.5 seconds
Deadbands:
  Gate GDB = 0.03 m (0.1 ft)
  Reset RDB = 0.024 m (0.08 ft)

P+PR CONTROLLER RESPONSE CHARACTERISTICS

Numerous mathematical model computer runs simulating the Bypass Drain were made to test the performance and stability of the P+PR automatic upstream control system. One of the computer runs for the Bypass Drain check No. 1, figure 6, is included to demonstrate the P+PR response characteristics for transferring a sudden change of flow downstream. Starting with an initial steady-state flow condition of 0.28 m^3/s (10ft^3/s), a step increase of 0.51 m^3/s (18 ft^3/s) inflow was made from the Yuma Desalting Plant 3.2 km (2.0 mi) upstream at time zero for a total flow of 0.79 m^3/s (28 ft^3/s). The increased inflow arrived at check No. 1 at time 18 minutes. The check No. 1 gate opened its first incremental deadband of 0.03 m (0.1 ft) at time 20 minutes to start transferring the increased flow downstream (fig. 6). The response characteristics of the P+PR controller, figure 6, shows how the modified gate deadband, GDB, procedure, explained in previous paragraphs, reduces the gate movement at time 192 minutes when the gate movement is opposite the previous movement direction. At time 360 minutes, the flow through the check No. 1 gate, 0.74 m^3/s (26 ft^3/s) is less than the total flow 0.79 m^3/s (28 ft^3/s) arriving from upstream. However, the water level is steadily rising and eventually the gate will open to increase the flow downstream. The gate "sawtooth" operation will continue to maintain a balance between the upstream inflow and the flow transferred downstream.

Other computer runs were made to simulate an emergency shutdown of the Yuma Desalting Plant, assuming operation at maximum (ultimate) capacity. The sudden transfer of the rejected desalting plant inflow downstream showed that the maximum water level rise above the check gate structures to be about 0.3 m (1.0 ft) and was within reasonable limits. The water surface return to the target depths for the new steady-state flow was within a reasonable time period for control stability. Computer simulation runs were also made to analyze the response characteristics for small, large, increased, and decreased flow changes at low and high initial steady-state flow conditions. The output of the simulation runs to obtain the response characteristics are not included, except for figure 6 , because a large volume of time history plots were generated. However, in all cases, the P+PR automatic upstream controller performed with stability, achieved satisfactory response characteristics, and automatically regulated all degrees of flow change satisfactorily, including on emergency shutdown of the Yuma Desalting Plant. Additional mathematical model studies were made to develop operational criteria (not included). The operational criteria developed will assist operators in the future and provide guidelines for both normal and emergency conditions. For normal operations, for example, flow increases should be limited to 2.8 m^3/s per hour (100 ft^3/s per hour) to limit water surface surges to 0.11 m (0.35 ft). Flow reductions should be

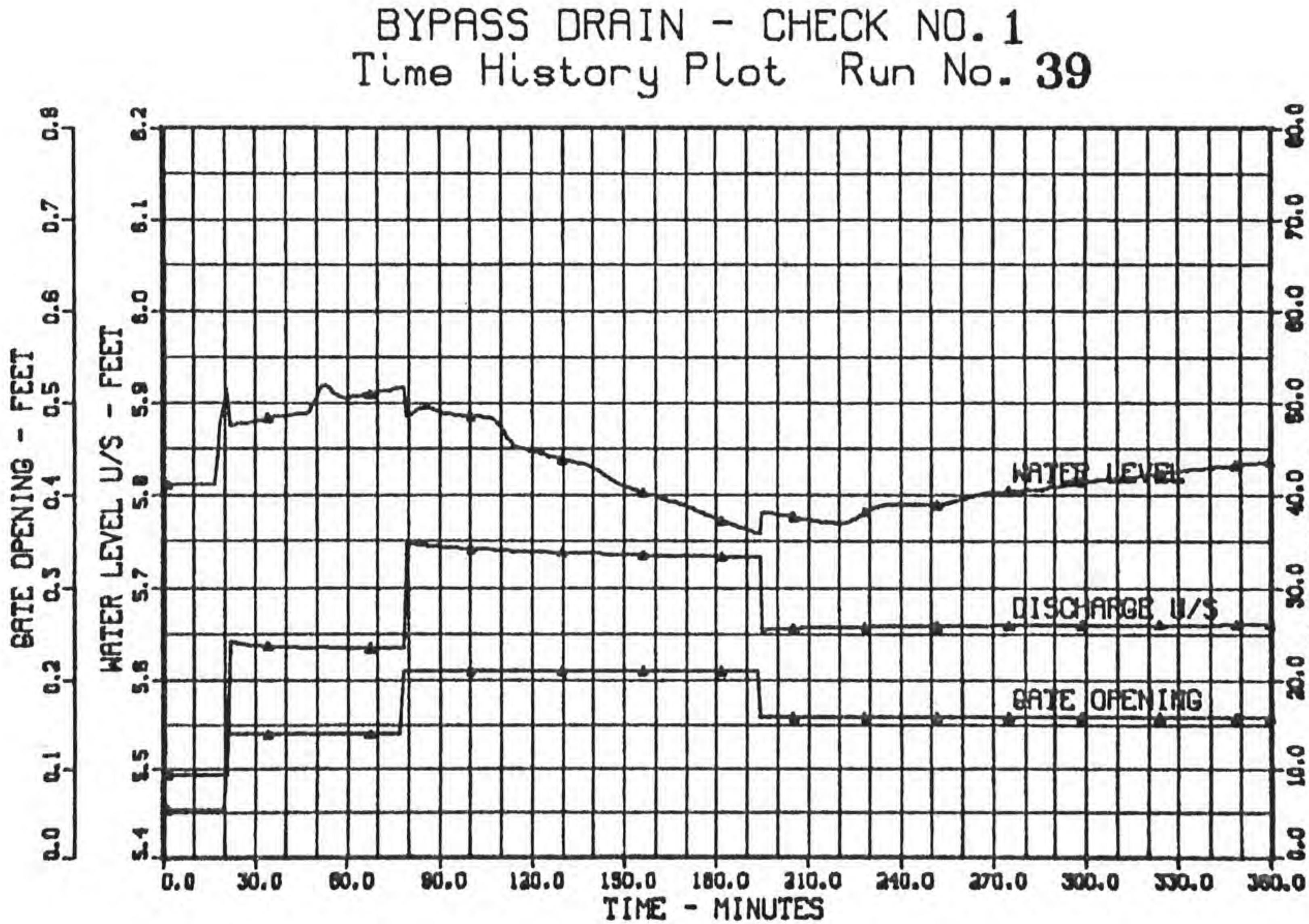


Figure 6 - Mathematical Model Simulation Time History Plot of the Bypass Drain with the P+PR Automatic Upstream Control System illustrating the controller performance transfering a sudden increase of flow from upstream to downstream at check No. 1.

limited to water drawdown criteria. For emergency conditions, sudden changes of flow, 5 m^3/s (177 ft^3/s) can be automatically regulated maintaining water level surges within reasonable limits of ±0.3 m (±1.0 ft).

ADVANTAGES OF P+PR UPSTREAM CONTROL

The P+PR control mode provides excellent upstream control for supply-oriented conveyance systems such as the Bypass Drain. The P+PR controller will automatically regulate all possible flow changes that can occur on the Bypass Drain without supervisory intervention, thus providing economic benefits. Unnecessary gate control responses that would be caused by wind-wave action and local disturbances can be eliminated by a filter having a time constant, TC, of 100 seconds. The "sawtooth" gate responses that are characteristic during steady-state flow conditions can be greatly reduced using the gate deadband, GDB, modification technique to reduce wear and tear on the gate hoist mechanism. The selection of the P+PR control parameters are relatively easy for upstream control applications.

DISADVANTAGES OF P+PR UPSTREAM CONTROL

Although the P+PR control parameters are relatively easy to select, mathematical model studies should be made to verify the parameter selection, for the entire conveyance system. A rather large computer facility is required for the canal and controller mathematical model. Without mathematical model computer output capabilities, an extensive field prototype test program would have to be implemented to verify the P+PR control parameter selection. Automatic control of canal check gates will increase the wear and tear of the gate hoist mechanisms even with the use of gate deadband, GDB, modification technique.

SUMMARY AND CONCLUSIONS

The P+PR mode of control provides desirable water surface elevation response characteristics, and the speed of response is satisfactory. The P+PR is recommended as the best method to achieve a satisfactory automatic upstream control system for the Bypass Drain. The P+PR mode of control, with properly selected control parameters, will control with stability any degree of flow change without supervisory intervention providing economic benefits. This includes, for example, an emergency shutdown of the Yuma Desalting Plant when operating at maximum capacity. An electronic filter is required to modify the output of the water surface sensor to eliminate unnecessary gate control responses that would be caused by wind-wave action and local disturbances. A technique of reducing the "sawtooth" gate responses that are characteristic during steady-state flow conditions has been developed. The technique defined as "GDB modification" should be implemented to reduce wear and tear on the gate hoist mechanism. Mathematical model studies should be made to establish operating criteria and guidelines to assist the operator for normal and emergency operating conditions.

The analysis of an automatic upstream control system for the Bypass Drain presented in this paper is the first major effort made in this regard, and the study was very beneficial. The selection of the P+PR control parameters is relatively easy. The study developed a digital filter and a technique to reduce the sawtooth gate response characteristics, labeled GDB modification, during steady-state flow conditions. The digital filter and the GDB modification technique can be used with all modes of automatic control that adjust check gates where logic circuits are available in mini or micro computers.

The analysis of the P+PR method applied to the automatic upstream control concept shows that a stable, self-regulating conrol system which maintains a reasonably constant water surface elevation, can easily be achieved in all canal reaches. The P+PR method developed in this report has application to other canal systems wherever the upstream control concept is required; that is, the transfer of inflow changes from upstream to downstream.

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APPENDIX I

Summary of the Bypass Drain Description and Physical Properties

The Bypass Drain will be a continuation of the existing Wellton-Mohawk Main Outlet Drain Extension. Brine waste from the Yuma Desalting Plant will be conveyed through the drain extension to a bifurcation structure located at the Morelos Dam, where the Bypass Drain begins, a distance of 3.2 km (2.0 mi). The brine waste and excess drain extension flows will be diverted through the bifurcation structure and conveyed to the United States-Mexico International Boundary by the Bypass Drain a distance of 25.8 km (16.0 mi). The beginning of the Bypass Drain, check No. 1 at the Morelos Dam, is located about 8 km (5 mi) west of Yuma, Arizona, and ends at the United States-Mexico International Boundary near San Luis, Arizona. South of the International Boundary, the Bypass Drain continues to the Santa Clara Slough, Gulf of California.

The U.S. segment of the Bypass Drain has four 3.7-m (12-ft) wide radial check gate structures, and four reaches (table 2), each 6.6-km (4.1-mi) average length. A free-flow, 6-m (20-ft) Parshall flume is located at the end of the U.S. Bypass Drain. The maximum capacity of the Bypass Drain is 10.0 m^3/s (353 ft^3/s).

Table 2. - Bypass drain physical properties

Reach No. 1/	Reach length,		Accumulated length,		YT design depth,	
	km	(ft)	km	(ft)	m	(ft)
1	7.2	(23,650)	7.2	(23,650)	1.85	(6.06)
2	6.7	(21,838)	13.9	(45,488)	1.65	(5.41)
3	5.9	(19,450)	19.8	(64,938)	1.65	(5.41)
4	5.9	(19,485)	25.7	(84,423)	1.65	(5.41)

1/ All reaches: Capacity 10 m^3/s (353 ft^3/s)
Bottom width 3.66 m (12.0 ft)
Side slopes 1.5:1