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INVESTIGATION OF THE PHYSICAL CHARACTERISTICS OF AN AUTOMATICALLY OPERATED HINGED OVERSHOT GATE

by

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The undersigned certify that they have read and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Investigation of the Physical Characteristics of an Automatically Operated Hinged Overshot Gate" submitted by Mr. Richard D. Carnduff in partial fulfilment of the requirements for the degree of Master of Engineering.

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ABSTRACT

Methods of automatic control for irrigation conveyance systems found in the literature tend to be forms of Floating Control, Proportional Control or Proportional Plus Proportional Reset Control. All physical modelling or field applications for these cases involve undershot sluice or radial gate structures. A single recent work of research related to the overshot gate has been done at the University of Calgary by computer modelling simulation.

The pivoting overshot gate has found wide acceptance in southern Alberta to provide checking action for purposes of upstream deliveries. This type of structure is easily adaptable to automated operation. In the University of Calgary hydraulics laboratory, a rectangular flume with a small pivoting gate was tested under upstream automatic control to observe the physical characteristics of this type of installation during non-submerged conditions. Using SAFE BASIC programming language, Floating, Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD) and Proportional-Integral-Derivative (PID) Control methods were tested using a programmable controller manufactured by Control Microsystems, called MiniSAFE.

For each method, a range of control parameters was tested from one extreme response (flat) to the other (unstable). Relationships were developed for control parameters that provided optimum water level responses, which were assessed on the basis of frequency of gate movement, degree of water level

cycling about the set point and duration required to achieve steady state conditions. P, PI and PID Control methods provided the most acceptable results. PID Control was found to give the best response characteristics because it has the most flexibility in programming to adapt to a range of situations.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

Page

Page

Page

Page

LIST OF PHOTOGRAPHIC PLATES

NOTATION

L	Horizontal distance of gate crest from its hinge.
P	Length of gate measured along its axis.
W	Vertical height of gate crest from the floor of the flume.
z	Fixed height of gate hinge above the flume's floor.
H	Height of the energy line above the gate crest.
h	Height of the water surface above the gate crest.
Y	Depth of water.
dy	Differential depth.
WL	Target water level, also referred to as the controller set point.
e	Error in water level, which is the difference between WL and Y.
v	Average flow velocity.
g	Acceleration due to gravity; used as 9.81 m/s^2 or 32.2 ft/s^2.
θ	Gate angle, measured relative to the horizontal position.
Δ	Symbol used to denote a change (difference) in the quantity appended (Example: Δt, $\Delta\theta$ and ΔSP).
t	Time.
dt	Differential time.
c	Rate of gate movement about its axis.
K	Proportional correction coefficient.
RE	Integral correction reset time.
RA	Derivative correction rate gain.
m	Total correction value.
TW	Waiting time period between gate adjustments.
Q	Flow rate.

DB Deadband, which is the maximum allowable error without requiring a correction in water depth.

SP Controller set point, also referred to as the target water level.

CHAPTER 1.0

INTRODUCTION

The hinged or pivoting gate is one of the more popular types of channel conveyance control structures used on irrigation projects in Southern Alberta. Its application is primarily to control the depth of water upstream to facilitate the lateral diversion of water supplies. Used as either a check structure or drop-check structure, it is found in a variety of canal system sizes, but it is most popular on smaller canals due to economics of construction. Plate 1.1 illustrates a typical structure used in Southern Alberta. It is a check-drop in what would appear to be distributary canal (Manz, 1987). A turnout structure is located immediately upstream of this structure which supplies water to a farm unit.

The pivoting gate operates just as its name implies. The gate, which is essentially a weir, is raised or lowered by rotating it about a hinge fastened to the structure floor. Figure 1.1 is a sample illustration of a gate manufactured by Armtec Construction Products, who supply many of these gates for Alberta irrigation projects. The cable and winch mechanism shown is the normal means of moving the gate. During irrigation deliveries it is operated for two reasons:

1. Upstream flows have increased or decreased caused by changes in the water demand, or

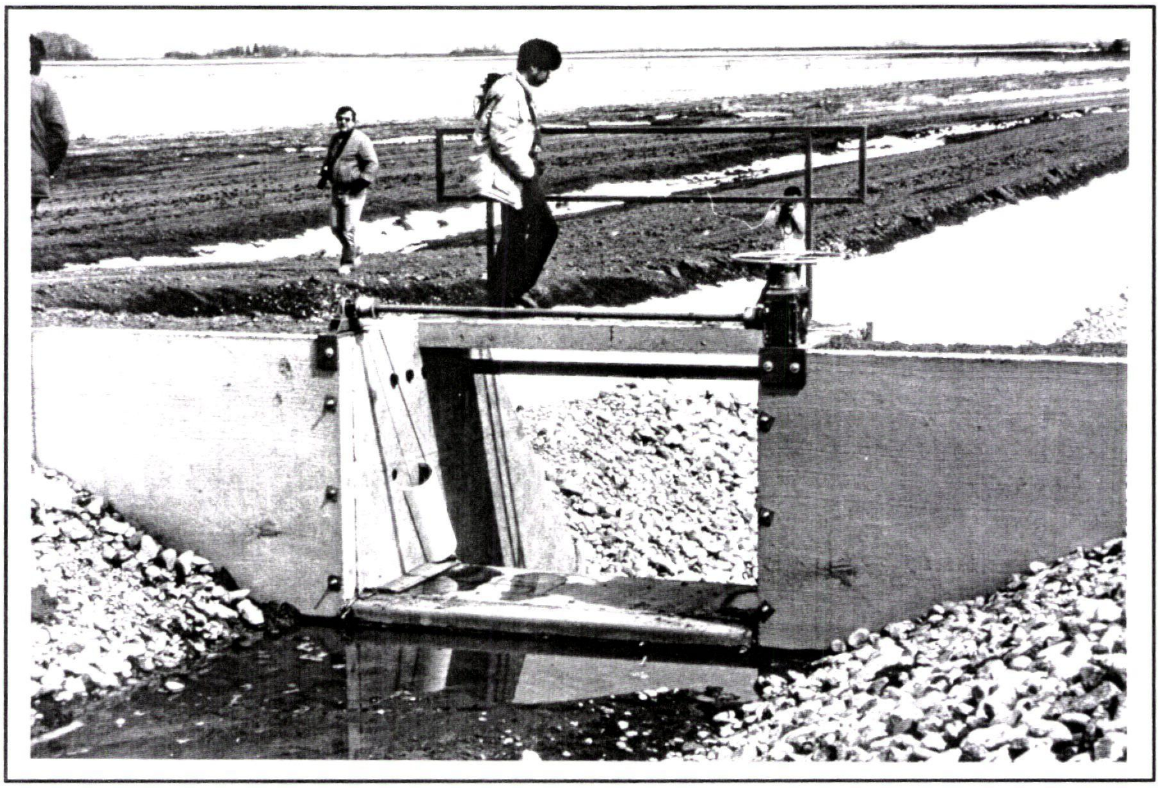


Plate 1.1 - Pivoting overshot gate in a Southern Alberta irrigation project.

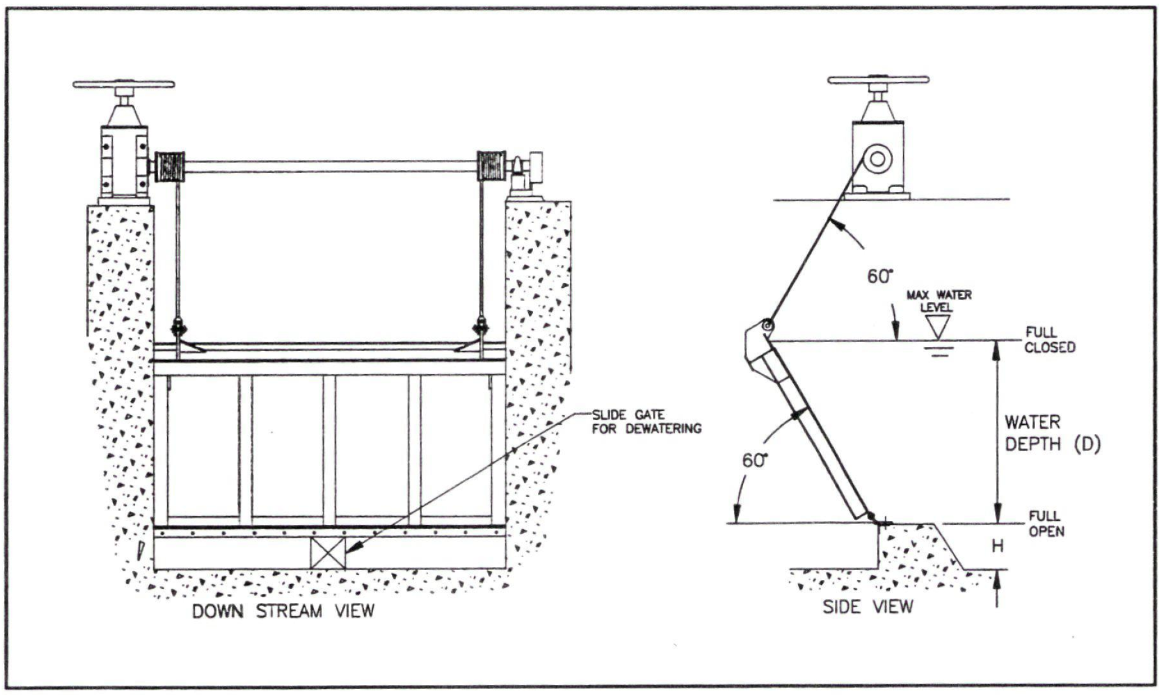


Figure 1.1 - Typical Pivoting Overshot Gate (Armtec, 1989)

2. The water level may be altered to suit changes in the location of upstream diversions.

Regardless of whether the structure is operated by a ditchrider as part of a larger delivery system, or whether it is serving only a single farm unit and is operated solely by the farmer, the structure requires human attention to operate and maintain it. The time associated with this can be appreciably reduced if the structure is automated so that only periodic servicing is required. These individuals judge the amount and frequency of gate adjustment required, based on personal experience and technical guidelines, and reset the gate accordingly. A return visit is made, usually at their convenience or schedule, to check the upstream water level or make another adjustment. To become a fully automated structure, the control method must be one that can replace these tasks with nearly equivalent functions. Supervisory attention will not be eliminated because certain operational problems will always require human intervention, such as resetting control parameters.

Equally important as the initial gate adjustment or correction is the response in upstream water level. The basis for effective gate operation and control is to achieve and maintain the target within a reasonable time period and accuracy; without unnecessary fluctuations and disturbances and without causing the canal banks to overtop. Before an automated structure is implemented in a canal system the operator should be fully cognizant of the way the controller responds to certain conditions and how the water level responds to gate adjustments. These characteristics of operation are the focus of this thesis.

CHAPTER 2.0

OBJECTIVES

The objective of this project is to investigate the physical characteristics of the pivoting gate under upstream automatic control. The research is to be conducted on a small scale prototype structure in the laboratory, with control operations performed by a programmable controller. Emphasis is placed on studying various combinations of proportional, integral and derivative control. The laboratory is preferred to a field simulation because system equilibrium can be quickly achieved, thus enabling numerous trial runs to be performed in a much shorter period of time. The work can be conducted without outside influences from normal canal operations or inclement weather, and the project is more accessible to the student, project supervisor and support university technical staff.

The research will provide valuable insight as to how the pivoting gate responds to various control algorithms. It will develop an understanding of the affects that control parameters have and the relative importance of each, and how the upstream water level responds to gate adjustments. The procedures used in this study can be adopted as a guide to field tests or applications.

CHAPTER 3.0

BACKGROUND REVIEW

Automation of irrigation systems is very common, particularly in the area of turf sprinkler systems. Whether it is for turf or agricultural purposes, the distribution and application of water is controlled primarily by the time or duration of each period of irrigation, referred to as a "set". Small canal systems which deliver water to one or more on-farm systems are referred to as distributary conveyance subsystems (Manz, 1987). For the most part, successful automation of these systems has been achieved by timer controlled check gates to facilitate diversion of water to the farm units (Humpherys, 1967; Humpherys, 1969; Jensen, 1983). Humpherys (1969) further describes check gates designed to operate by hydrostatic pressure. This type of gate is balanced by the upstream water level. By its own weight, the gate is closed until the water level rises to the design level, above which the hydrostatic force (upstream) causes the gate to pivot open about a horizontal axis. Water flows over the top of the gate, which will remain open so long as the flow overtop continues.

Higher order systems such as lateral subsystems and main canals (Manz, 1987) are not suitable for timer controlled gates. They service a large number of users and are faced with more complex conditions of operation. Individual structures may provide either upstream or downstream control functions, which can change depending on conditions. Several control systems have been developed and applied for both types of operation.

On the Columbia Basin Project in the State of Washington (USA), an automatic controller was developed to provide constant water level control (upstream) of its vertical sluice gates in response to changes in flow (Gray and Humes, 1972). Initially, the control mechanism consisted of a float-controlled cam and two micro-switches which turned power on/off to an electric motor that actuated gate movement. As the water level rose, the cam rose in elevation until it tripped the upper switch, thus causing the gate to be raised. The reverse would occur if the water level dropped too low. Power to the motor was controlled by a timer which regulated the amount of gate movement at any single time. This was done to dampen oscillations of the water level in the upstream channel. Oscillations still occurred in some installations during gate closing. It was reasoned that the gate action caused velocity shock waves/surges, primarily during gate closing. Accordingly, a second timer was added to provide a slower rate of gate closing; the first one being retained for gate opening. This modification effectively solved the oscillations in those cases.

A portion of the Columbia Project had a high frequency of check structures, which resulted in short distances between structures. The modified float system was not sensitive enough to deal with surges in these short reaches. It was observed that gate adjustments were still being made owing to the transient water levels, and the system behaved in a hunting fashion for the desired gate setting. Further modifications were made which included additional micro-switches and a drag clutch. This anti-hunt mechanism effectively improved the control action and water level response.

This type of controller developed in the Columbia Basin has been referred to by others as the Little-Man controller (Dedrick and Zimbelman, 1981; USBR, 1973). USBR further defines it as single-stage floating control with SOT/SRT (see Chapter 4.0), which is best suited where water level response lag is not appreciable. They further state that it is preferred for upstream control rather than downstream control.

Harder, Shand and Buyalski (1972) describe a proportional controller called HyFLO, or Hydraulic Filter Level Offset, for downstream control of an undershot gate. The term "offset" is used to describe the difference between measured water level and target water level, which in this instance was located at the next downstream structure. The offset was processed through a filter to an analog computer, which determined the required gate opening and signalled an electric motor control accordingly. An offset of zero or near zero was obviously desired, but this would result in a highly sensitive gate operation (to disturbances), which would have caused oscillatory waves (surges). The solution was to reduce the sensitivity, which was the gain of the control system, using the filter. The filter used was a small capillary tube connected between the main stilling well and a secondary well in which the level sensor was located.

The required gain and filter parameters for the HyFLO controller were calculated theoretically and then checked by computer simulation. The controller was tested in the field on a reach of the Corning Canal, a feature of the Central Valley Project in California. The desired gate opening was calculated by multiplying the offset with the gain factor, and this was compared to the actual gate opening. If the difference in gate opening, ΔG, was less than a deadband value (0.03 m in this case) no gate adjustment was initiated. Otherwise, gate movement would occur in the proper direction until $\Delta G=0$. From the field trials, a high degree of control was attainable, but it was felt that "there was an inherent delay in the total response at the headworks to the canal" (Harder, Shand and Buyalski, 1972).

The HyFLO controller was basically a type of proportional controller. Following the Corning Canal work described above, the hydraulic filter was replaced with an electric time delay, and the controller was renamed the Electronic Filter Level Offset (EL-FLO) Controller (USBR, 1973). A further modification was proposed by adding reset action to the EL-FLO controller, which was investigated for the brine bypass drain from the Yuma Desalting Plant in Arizona (Buyalski, 1977). This control method was renamed Proportional Plus Proportional Reset (P+PR) mode. The desired gate opening was determined by adding the gate openings for P control and PR control which were computed separately. Computer modelling was performed to test the control theory. A digital filter was used to simulate a hydraulic filter. In addition to the gate deadband, a water level deadband was incorporated into the reset control calculation.

ALSTHOM Inc. has developed a NEYRTEC system of automated radial gates for level control applications, which operate on the basis of floats and counterweights for balance. They offer an AMIL type for upstream control and AVIS (surface) or AVIO (orifice) types for downstream control. Their operation is described by Merriam (1977) and Goussard (1987).

The California Aqueduct is fitted with automatic controllers at some of its radial gate check structures (Frederikson, 1969). At those locations, one gate bay in each structure provides the automatic water level control. Initial adjustments are made by the ditchriders, with refinements in gate settings provided by the automated gates. Problems have been experienced in the canal reaches with waves and set-up caused by wind, plus hydraulic transients caused by gate adjustments (DeVries and Amorocho, 1973). The controllers on the check gates (upstream control) were said to be contributing to the transient problems because several were operating in series. The control methods were proportional plus reset types. Each change in water level and gate movement affected the response at the next downstream structure, which resulted in an accumulation of over adjustments.

In spite of this controller problem on the California Aqueduct, it was concluded by the above authors and others (Dewey and Madsen, 1976) that the major cause of hydraulic transients was due to the structures being manually operated in a series fashion. A time delay occurred in operation of the structures because of the time it took for the ditchriders to travel between each. A suggested remedy was either simultaneous or timed gate adjustments, which would necessitate some form of automatic operation.

All of the previous examples of automatic control relate to vertical sluice or radial type gates. Only one example of automated control of a pivoting overshot gate is found which occurs in two sources; that of Manz and Schaalje (1991) and Schaalje (1991). This work involved the comparison of the Little-Man, EL-FLO and PID controllers in providing upstream control of a pivoting check structure on an irrigation canal, using computer model simulation. The relevant characteristics used to compare the controllers were accuracy to which water level is controlled, degree of overshooting the target level and instability. No conclusion was made regarding the preference of any one controller over the others for this type of application.

CHAPTER 4.0

CONTROL THEORY

4.1 Feedback Control Principle

A closed loop feedback control system was used for this project, which necessitated two inputs to the controller:

- upstream water depth
- gate position

The upstream water depth is essential in a feedback system for upstream control because the difference between measured (actual) water level and target water level (set point) determines the gate adjustment or setting. The gate position, which in this case is its vertical angle relative to horizontal, is only warranted for the pivoting gate because the change in gate height varies throughout its range of positions. If the gate were a vertical type (undershot, overshot or radial) then the change in gate height would correspond exactly with the change in its position, and the gate position input would not be essential to the controller.

This rationale would not be valid if the control system were similar to the HyFLO or EL-FLO systems. With these controllers, gate adjustments are made until its position corresponds to a calculated desired opening, which necessitates a gate position input to the controller.

Because the upstream water level determines the gate setting, the system is defined as upstream control. Alternatively, using downstream control would mean that the downstream water level determined the gate setting required, which essentially is a flow control system. Upstream level control is most commonly used in irrigation projects where diversions upstream of the control structure are made, and an accurately regulated depth of water is achievable to ensure that stable deliveries are possible.

4.2 Control Output Principle

The controller used in this project is capable of providing both analog and digital output control. However, the gate operation must be done on the basis of digital output. Chapter 5.0 describes the equipment in detail, whereas the following explains the fundamental difference between analog and digital control.

With analog output, an electrical output signal is sent which is in proportion to its maximum possible value. This is illustrated in Figure 4.1 which shows an output signal, measured as a percentage of its total value, varying relative to time. The value of the output determines the setting of the control element in a feedback control loop. A simple example to illustrate this point is a heater (control element) used to regulate the temperature of liquid in a vessel, illustrated in Figure 4.2. The controller provides an electrical output to the heater which in turn provides a corresponding level of heat to the fluid, referred to as the

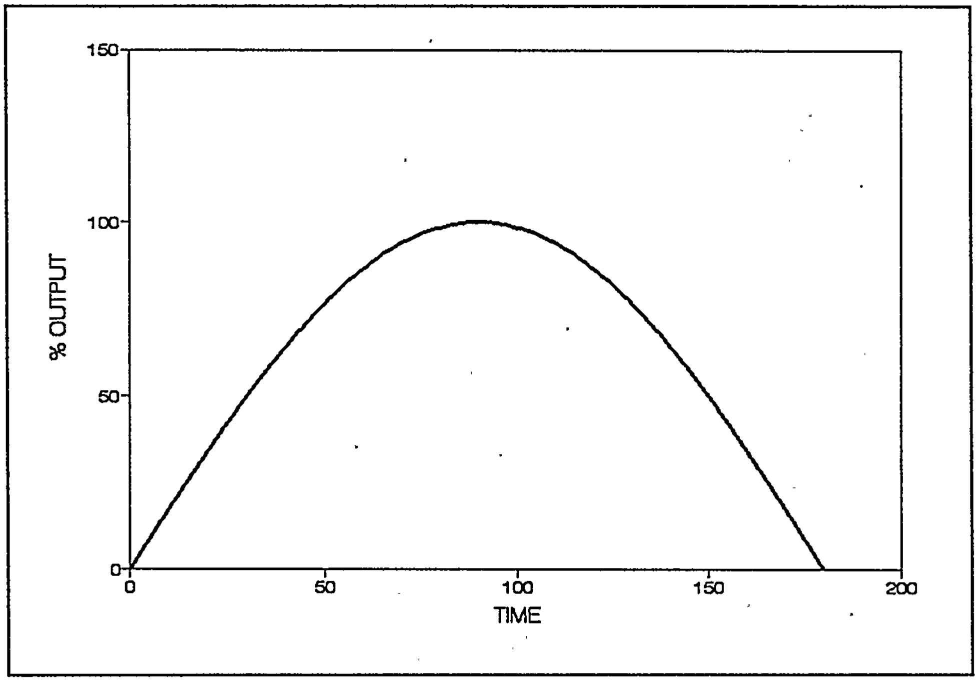


Figure 4.1 - Analog Output Control

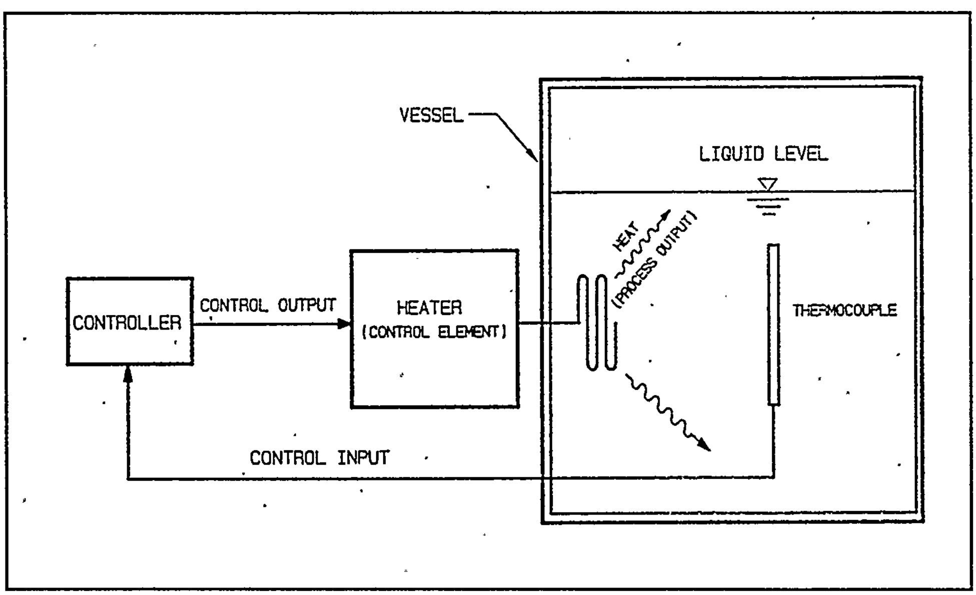


Figure 4.2 - Temperature Control in a Vessel

process output. If the temperature of the fluid rises above or below the desired set point temperature, the controller decreases or increases its output, resulting in a corresponding reduction or increase in heat output.

In the case of the pivoting gate, each value of analog output will correspond to a specific gate setting or height. However, as mentioned previously, the apparatus for this project is designed for digital control operations.

With digital output the output signal is either zero or its maximum value, and the duration (time) of output occurs as a series of pulses. Shown on Figure 4.3, this is referred to as time proportioned output which comprises a series of equal time periods T, each with proportions of on-time and off-time. The control element is turned on and off at various intervals of time. For the apparatus used in this project, an on-time results in electric power turned on to raise or lower the gate. During off-time the power is turned off, and the gate comes to rest at an arbitrary position.

4.3 Two-Position and Floating Control

Two-position control and floating control are terms used by the United States Bureau of Reclamation which describe two basic forms of control used on Bureau projects (USBR, 1973). Two-position control represents the most simple method because the control element is at one of two extreme operating positions; fully open or fully closed. Typically this describes

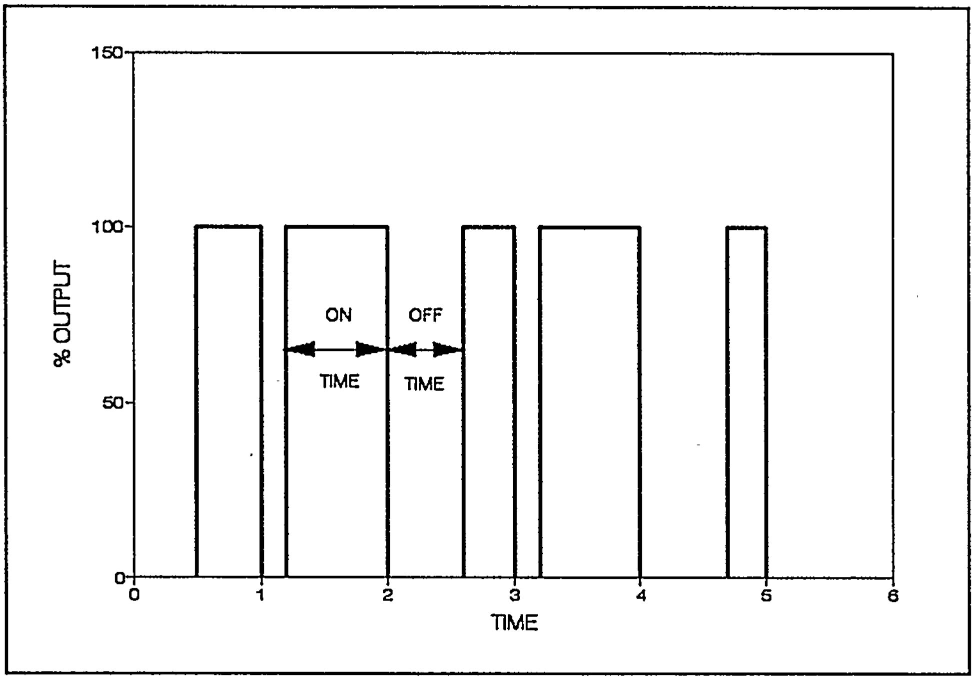


Figure 4.3 - Time Proportioned (Digital) Output Control

an on-off operation which is characteristic of a fixed speed pump or valve. In terms of this project, the definition would mean that the pivoting gate, which is the control element, would change from its lowest position (open) to its highest checking position (closed) at an instant. From a practical standpoint the gate cannot slam open or closed, so this term does apply to gated structure control. Also, this type of application limits the upstream water level to only two positions for every value of discharge.

Floating control differs slightly from two-position control because the gate changes at a constant speed between its two extreme positions, and it is allowed to rest at intermediate positions. The speed of gate movement is important. If it is too rapid the gate will closely resemble two-position control and cause hydraulic transients (velocity waves) to occur, thus causing unstable gate movements. If the gate action is too slow it will respond slowly to dramatic or frequent changes in the upstream hydraulic condition.

Rapid Gate movement is preferred because it responds faster to changes in the upstream condition. It is easier to reduce large gate movements if transients occur than it is to improve gate movements too slow. This is accomplished by incorporating timers which regulate both the time of gate movement and time of reset (no gate movement); referred to as set-operate-time/set-reset-time (SOT/SRT). Other devices can be incorporated to improve the operation, such as proportional speed and anti-hunt devices. The Little-Man controller (Chapter 3.0) is an example of this type of control.

Floating control with SOT/SRT is the starting form of control used for this project. Unlike the Little-Man controller, a second timer is not used to provide a slower rate of gate raising (closing). The anti-hunt feature is simulated by incorporating a waiting time period between adjustments.

4.4 Basic Control Algorithm

The most logical algorithm for this type of structure is simply the translation of error (e) between target water level (WL) and actual depth (Y) to a corresponding equal adjustment in gate height in the appropriate direction. In the literature, the term "offset" is also used to describe this difference in levels. The rationale for this reasoning follows.

The hydraulic relationship for flow over the pivoting gate is described by the basic weir equation

$$Q=CB\frac{2}{3}\sqrt{2g}H^{3/2} \qquad [4.1]$$

where C = coefficient of discharge

B = length of weir crest

H = hydraulic head over the weir, including approach velocity

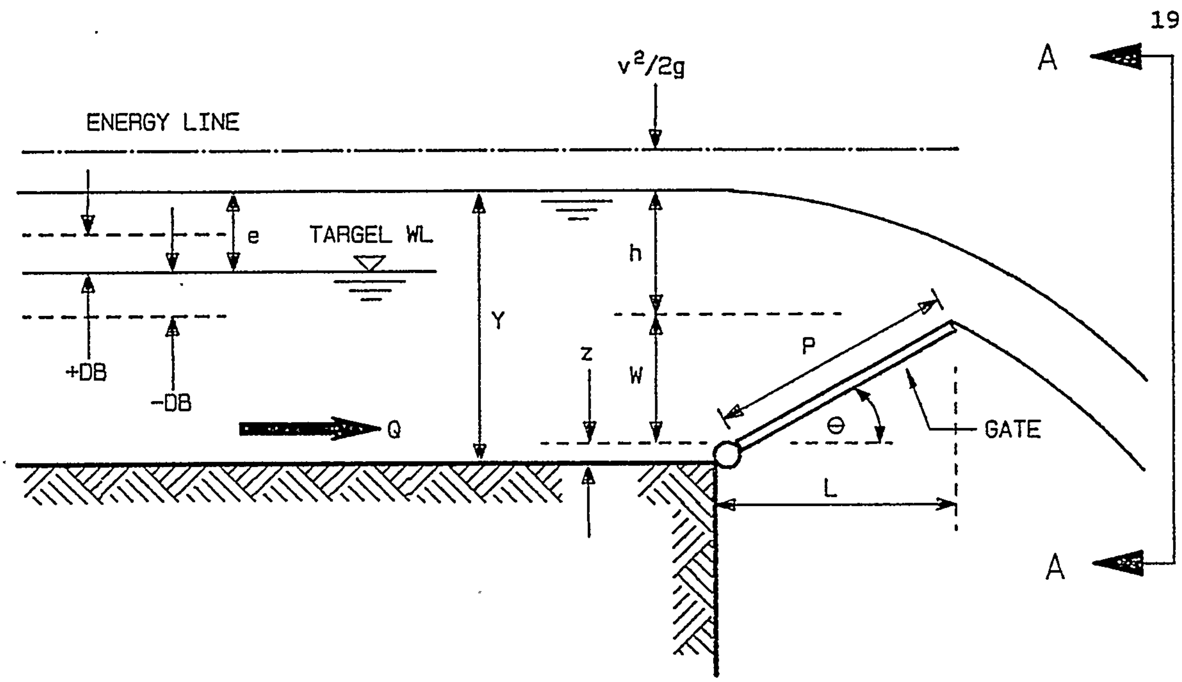
This nomenclature is illustrated in Figure 4.4.

Consider an initial gate setting represented by subscript 1 and a corrected gate setting represented by subscript 2. At any instant in time, when a gate adjustment is to be executed, the value of Q is constant (i.e. $Q_1=Q_2$). Dimension B does not change, and g is a constant. Therefore the following relationship is derived from Equation 4.1:

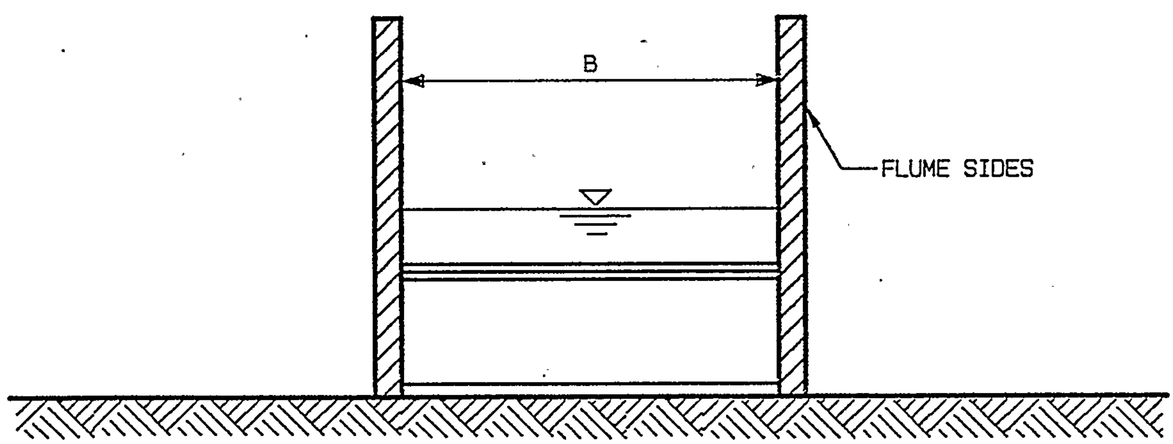
$$C_1H_1^{3/2}=C_2H_2^{3/2} \qquad [4.2]$$

The pivoting gate, or weir, is unique in its relationship with the discharge coefficient because the coefficient changes with the weir setting. At and near to the vertical position the gate behaves like a sharp crested weir. As it approaches the horizontal position the gate behaves more like a broad crested weir.

In spite of this characteristic in discharge coefficient, it is assumed that when a gate adjustment is necessary, the coefficient at initial gate



Profile Elevation View



End View - Section A-A

Figure 4.4 - Flow Over a Pivoting Weir

setting is equal to the coefficient at final (corrected) gate setting (i.e. $C_1=C_2$). This simplification is justified when minor gate adjustments are required because the differences in coefficient are too small to affect the accuracy of gate adjustment computations. In situations when large gate adjustments are made, it is reasoned that the error will only be significant initially, and that this error will be corrected by subsequent small adjustments as refinements are made in the gate setting.

It thus follows from Equation 4.2 that $H_1=H_2$. The total head H is equal to the sum of h (Figure 4.4) and the velocity head, $v^2/2g$. Relative to h, the velocity head will be sufficiently small that it can be neglected. It thus follows that $h_1=h_2$. Therefore, the required gate adjustment is equal to the error between target and actual water levels.

Referring to Figure 4.4, the following relationships are developed:

$$W_1=P(\sin\theta_1) \qquad [4.3]$$

$$h=Y_1-W_1 \qquad [4.4]$$

$$e=Y_1-WL \qquad \text{and} \qquad Adjustment=e \qquad [4.5]$$

$$\therefore W_2=W_1-e=P(\sin\theta_1)-e \qquad [4.6]$$

$$L_2=\sqrt{(P^2-W_2^2)} \qquad [4.7]$$

$$\theta_2=\arctan(W_2/L_2) \qquad [4.8]$$

$$\Delta\theta=\theta_1-\theta_2 \qquad [4.9]$$

Returning to the principle of time proportioned output discussed in Section 4.2, the controller must translate the change in gate setting to a period of on-time (Figure 4.3) during which the gate is raised or lowered the value of $\Delta\theta$. Therefore, consider the rate of gate movement (c) with respect to time (t):

$$c=\frac{\Delta\theta}{\Delta t} \qquad and \qquad \Delta t=\frac{\Delta\theta}{c} \qquad [4.10]$$

Equation 4.10 thus translates the measured error to a corresponding change in gate setting. The value of Δt is the on-time component of the time proportioned output. Because of the physical orientation and setup of the gate and motor, the rate of gate movement is not constant. However, to simplify the computations and programming, it was assumed that this rate was constant. During calibration trials (Chapter 6.0), this assumption was found to be reasonably valid.

4.5 Proportional (P) Control

Under proportional control the controller sends an output signal that is in proportion to the error:

$$p=K_c e+p_s \qquad [4.11]$$

where K_c = proportional gain

p = controller output

p_s = a constant

This is the classical equation found in the literature, but it is valid only for an analog output signal and not applicable to time proportioned output. In the case of the latter, the output must be either zero or the maximum output available. Accordingly, the equation is modified to suit time proportioned output. This is done by replacing the controller output term with a correction term (m):

$$m=K_c e+m_s \qquad [4.12]$$

Because the output is time proportioned, $m_s=0$. Otherwise there would always be a value of correction with subsequent adjustments, even when e=0. Therefore Equation 4.12 is written

$$m=Ke \qquad [4.13]$$

where K is now taken as the proportional gain.

This correction becomes the change in gate height which is equal to the value of the error, with the ± sign being preserved. It is translated to a period of controller on-time by Equation 4.10.

4.6 Proportional Plus Integral (PI) Control

A problem with proportional control is that it tends to cause steady-state errors. When large errors occur, the response in process value is slow. This can be overcome by adding integral or reset action to the control algorithm, thus creating proportional plus integral (PI) control. This is represented as

$$m = Ke + \frac{K}{RE}\int e\,dt \qquad [4.14]$$

where RE = reset time

dt = differential time

$\int$e dt = integration of all previous errors

Because the control algorithm does not operate continuously, the discrete forms of the integral and derivative terms are substituted to give

$$m = Ke + \frac{K\Delta t}{RE}\sum e \qquad [4.15]$$

In this equation, the term Δt is not the same as that used in Equation 4.10. The integral component adds correction in proportion to the size of the error, resulting in a quicker response time.

The literature is not clear on what time period (Δt) that Σe is applied over; whether it adds to itself continuously or is reset to zero after a fixed interval of time. It was assumed than Σe is reset to zero after each gate adjustment, so that previous errors would not influence the next execution of the control algorithm. This term became a summation of all errors at discrete intervals within the time period Δt.

4.7 Proportional Plus Integral Plus Derivative (PID) Control

Although integral control improves the response of the controller, it can cause the water level to oscillate about the set point. This can be minimized by reducing the proportional gain or increasing the reset time. However this causes a slower response which defeats the purpose of integral action. As an alternative, derivative control is added to eliminate the oscillatory response. This is represented as

$$m=Ke+\frac{K}{RE}\int edt-K(RA)\,\frac{dpv}{dt} \qquad [4.16]$$

where RA = rate gain

dpv/dt = rate of change in the process value with respect to time

Again, substituting the discrete forms of integral and derivative terms Equation 4.16 becomes

$$m=Ke+\frac{K\Delta t}{RE}\sum e-K(RA)\,\frac{\Delta pv}{\Delta t} \qquad [4.17]$$

The derivative term anticipates the response of the correction in process value (water level) by measuring its rate of change. If the response is small the derivative term is likewise small, thus allowing the other two terms to dominate. If the response is large, the derivative term is sufficient to dampen the other two terms, particularly integral action, so that oscillation does not occur.

Equation 4.16 differs slightly from the theory presented in various literature sources. First, the derivative term is subtracted rather than added. This is not significant since the value of RA is selected experimentally to provide the best control response, and the sign will be determined accordingly. Second, the derivative term includes the rate of change in process value (dpv/dt), rather than the rate of change in error (de/dt). Control Microsystems (1989) justifies this on the basis that if a change in set point were to occur, de/dt would be infinite, whereas dpv/dt is less sensitive to the set point change. Also, dpv/dt is more sensitive to disturbances in the process value.

CHAPTER 5.0

PROJECT APPARATUS

The apparatus used was one of two flumes already in operation in the Hydraulics Lab. It was already fitted with a pivoting gate, but some minor alterations were required to locate the gate at the end of the flume. Figure 5.1 illustrates its physical layout and dimensions. Details of the various components are described in the following sections.

5.1 Flume and Gate

The flume is constructed of clear plastic with aluminum framing, as shown in Plate 5.1. It is mounted on a table which is capable of altering the channel slope, although zero slope was used for this project. At the downstream end, a 13 mm thick aluminum plate with an upper knife edge is mounted to the bottom of the flume by a hinge so that it resembles a pivoting weir, shown on Plate 5.2. The top of the plate, in its vertical position, is about 288 mm ($11^{11}/_{32}$ in.) above the flume invert (including hinge). At a depth of 300 mm water will spill over the wingwalls. Consequently this depth was chosen as a maximum allowable depth for checking operations.

Water which spills over the plate falls vertically into a drainage chamber and out a floor drain. The chamber is sufficiently below the flume invert that at all times the tailwater is below the gate. This ensures that the gate always operates under non-submerged conditions.

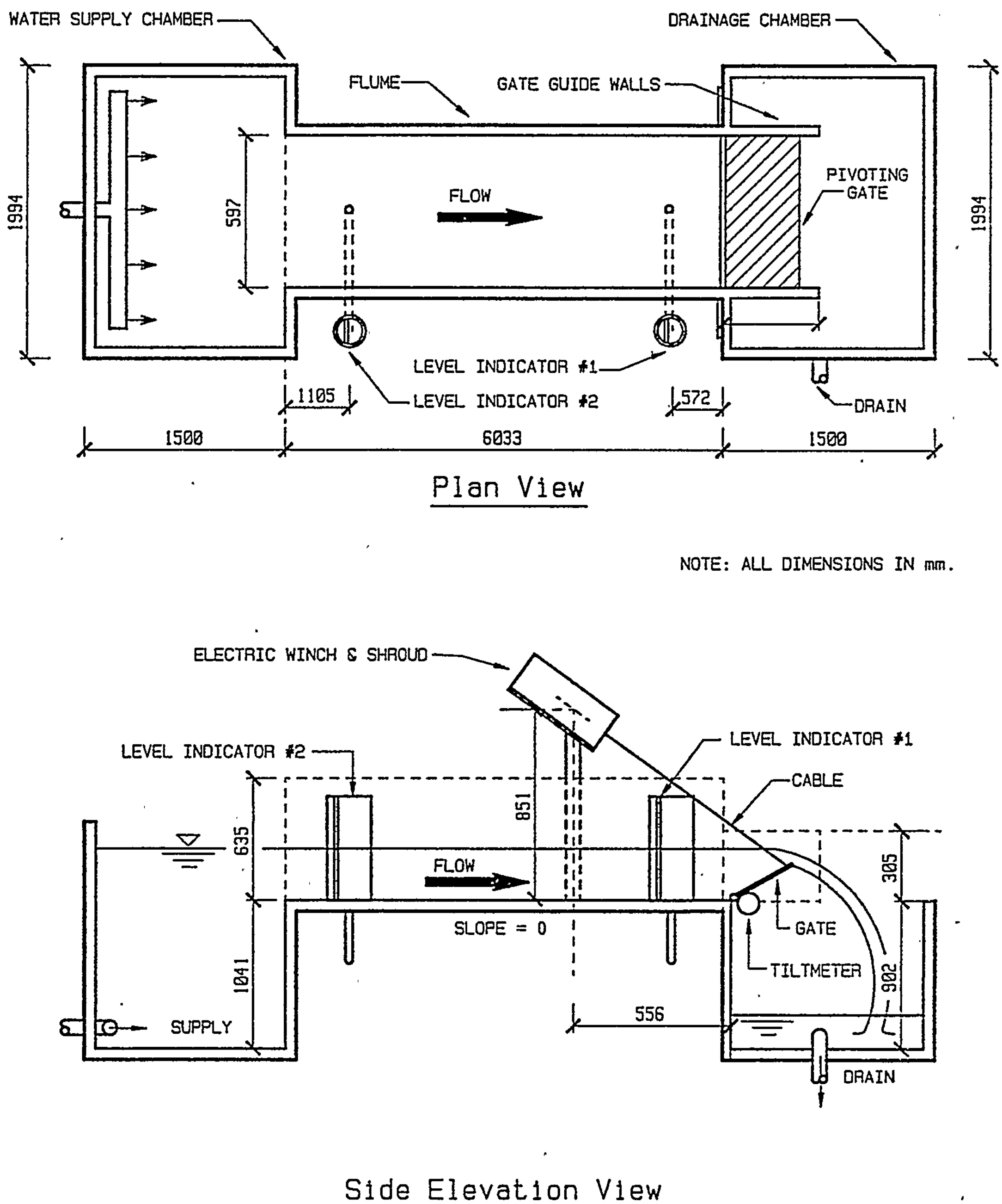


Figure 5.1 - Flume Layout

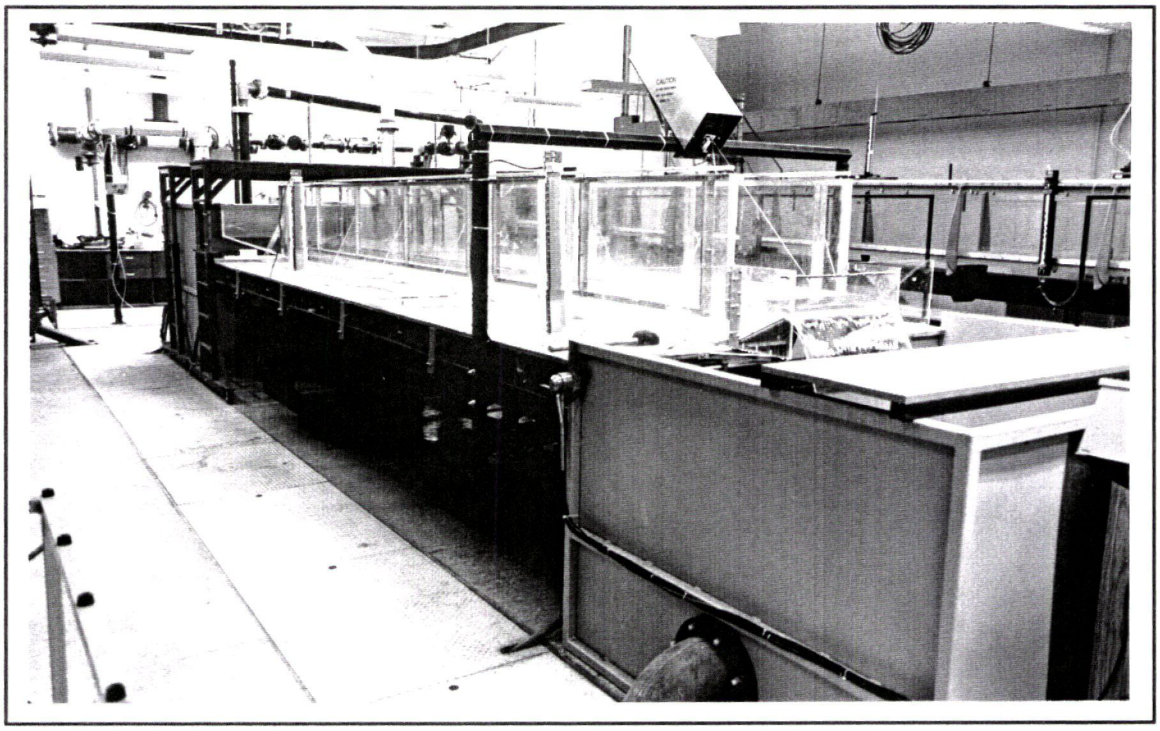


Plate 5.1 - Flume with water supply chamber at left and drainage chamber at right. Note level indicators along the side.

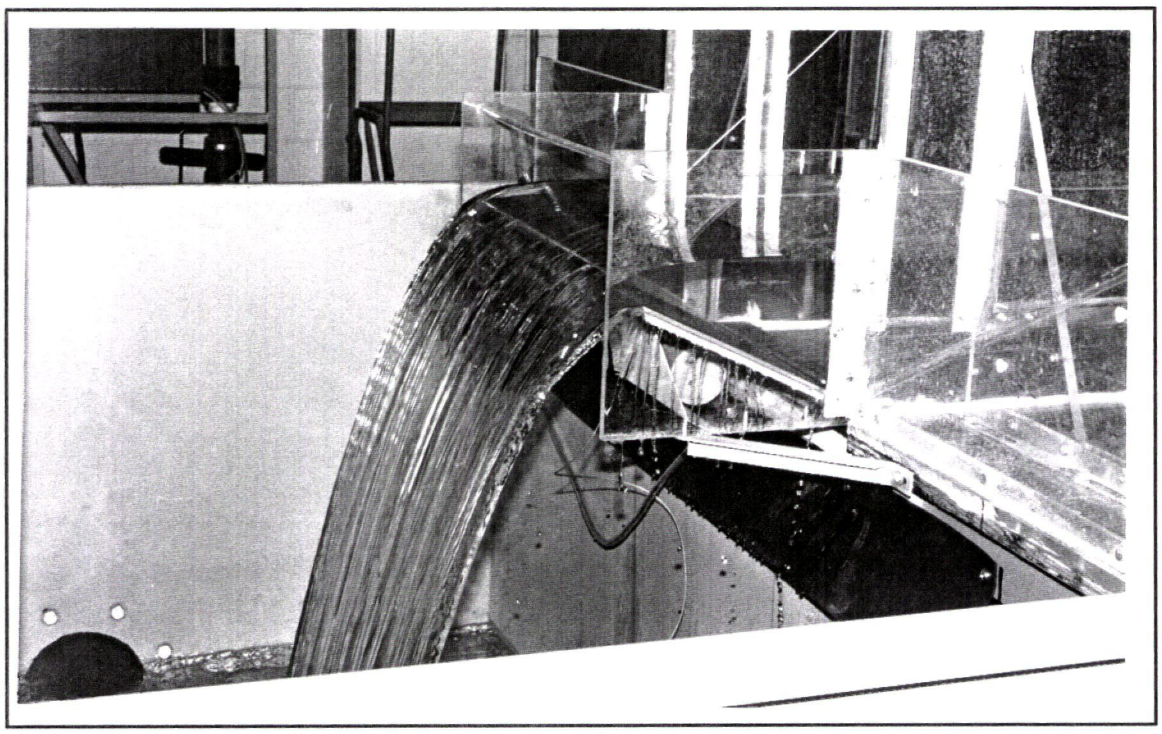


Plate 5.2 - Pivoting weir (gate) with flow going overtop into drainage chamber. Note drain pipe in lower left.

5.2 Water Supply

Water is pumped to a supply chamber at the upstream end of the flume where it flows by gravity down the flume, shown on Plate 5.3. This resembles a typical supply-diversion scheme found throughout Alberta irrigation projects. The chamber acts as a storage reservoir, which helps to stabilize fluctuations in deliveries.

The flow rate is controlled by a 100 mm Keystone butterfly valve with an EPI-TORC (electric) actuator. The actuator is regulated by a potentiometer control unit that can be adjusted manually or by the host computer (Section 5.7). The potentiometer setting varies between 0.0 (fully closed) to 10.0 (fully open), which corresponds to a voltage output of 1 V and 5 V respectively. Throughout the project experiments, only manual adjustments were made.

5.3 Gate Control Mechanism

The pivoting plate, or gate, was already configured for manual operation. Alterations were made so that it could be operated by an electric motor. This was accomplished by mounting a 110V electric winch on a frame above the flume as shown in Plate 5.4. A stainless steel cable was fastened between the mid-point of the gate near its top and wound around the winch's drum. When the gate is in a horizontal position, the vertical angle of the cable is 45°.

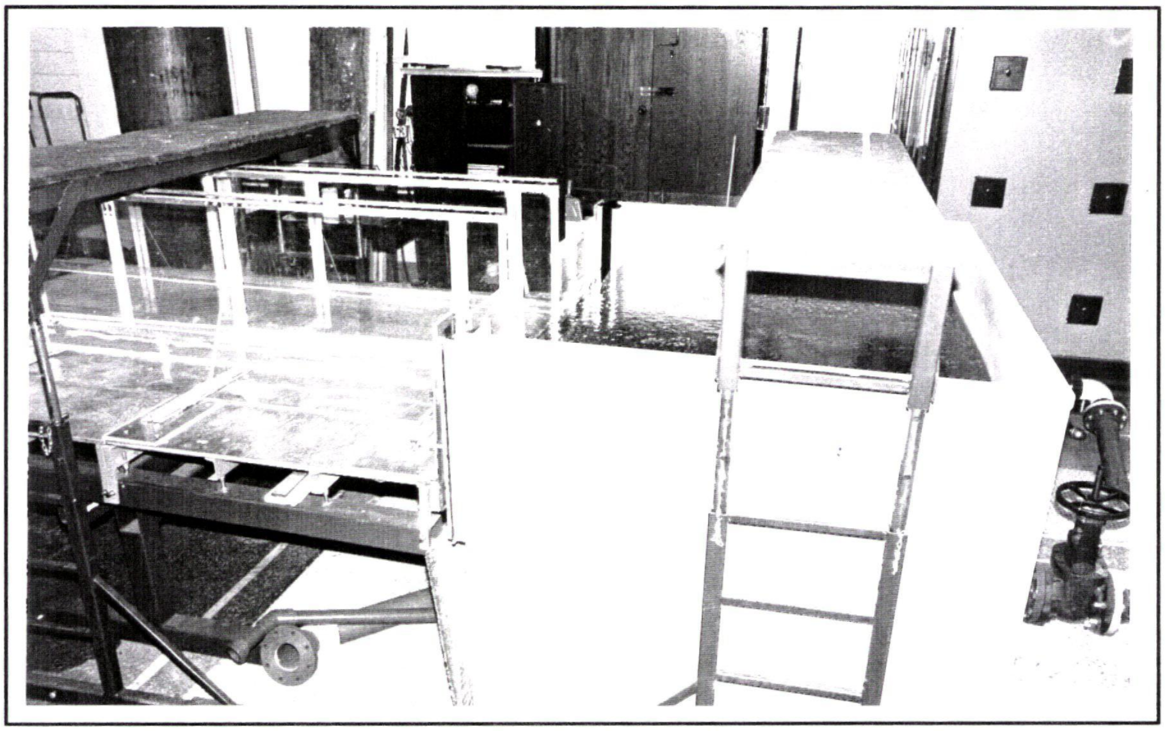


Plate 5.3 - Water supply chamber and entrance to flume.

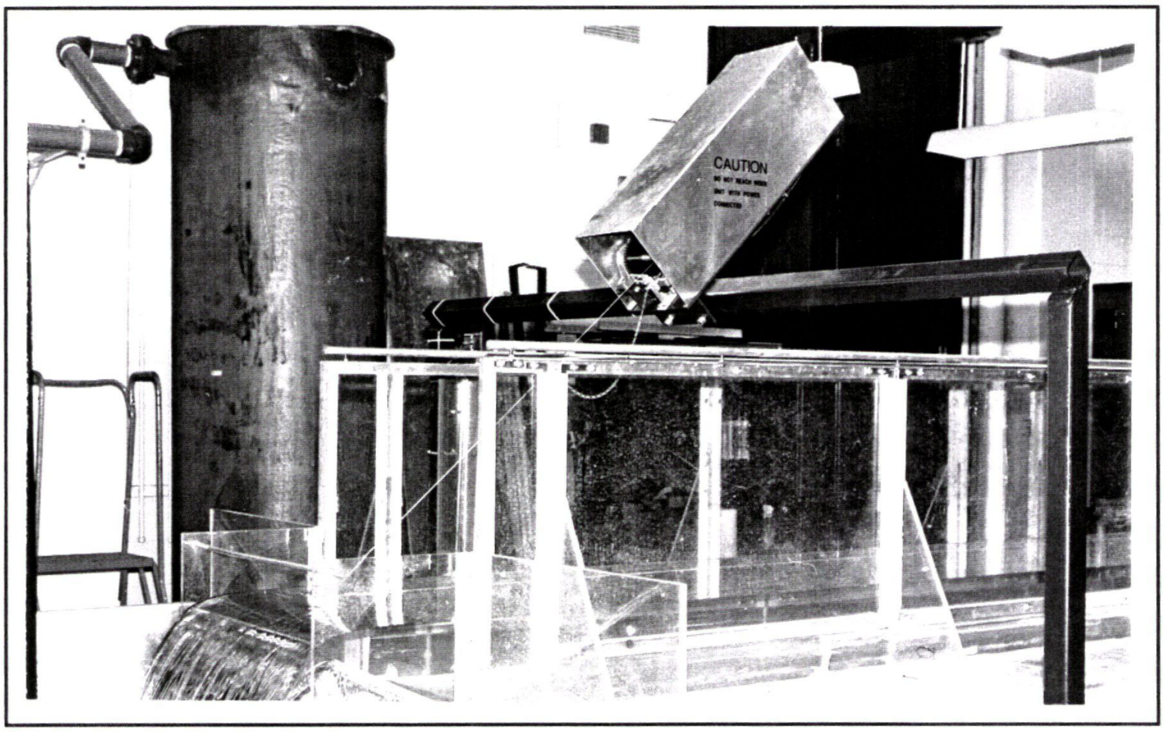


Plate 5.4 - Electric winch that moves gate.

The winch is capable of operating in forward or reverse directions so that the gate can be raised or lowered. This is regulated by a switch mounted in a separate Motor Control Box, shown in Plate 5.6. When the switch is in the open position and power is turned on, the winch operates in a forward direction (gate is raised). Conversely, when the switch is closed and power is turned on, the winch operates in a reverse direction (gate is lowered). The switch is actuated by a relay in the controller unit (Section 5.6).

A wiring diagram (schematic) of the switch and motor, as well as a sketch of the mechanical gear connections, are included in Appendix B.

Safety features are incorporated to prevent the gate from being lowered too far or raised too high. In the latter case, if the gate is pulled passed 90° from the horizontal position, the rubber side seals will lose contact with the gate guide walls (Figure 5.1). This will cause the gate to jam so that it cannot be lowered. To prevent the gate from being raised too far, an aluminum disk is fastened to the cable and a lever action micro switch is bolted to the winch frame. When the disk strikes the lever it activates the switch which turns the power off to the motor (at about 90°). To prevent the gate from being lowered too far, a brass chain is fastened between the micro switch and disk. At about -3° the cable is drawn taught which actuates the micro switch. Again, this turns power off to the motor.

These safety features are shown on Plate 5.5.

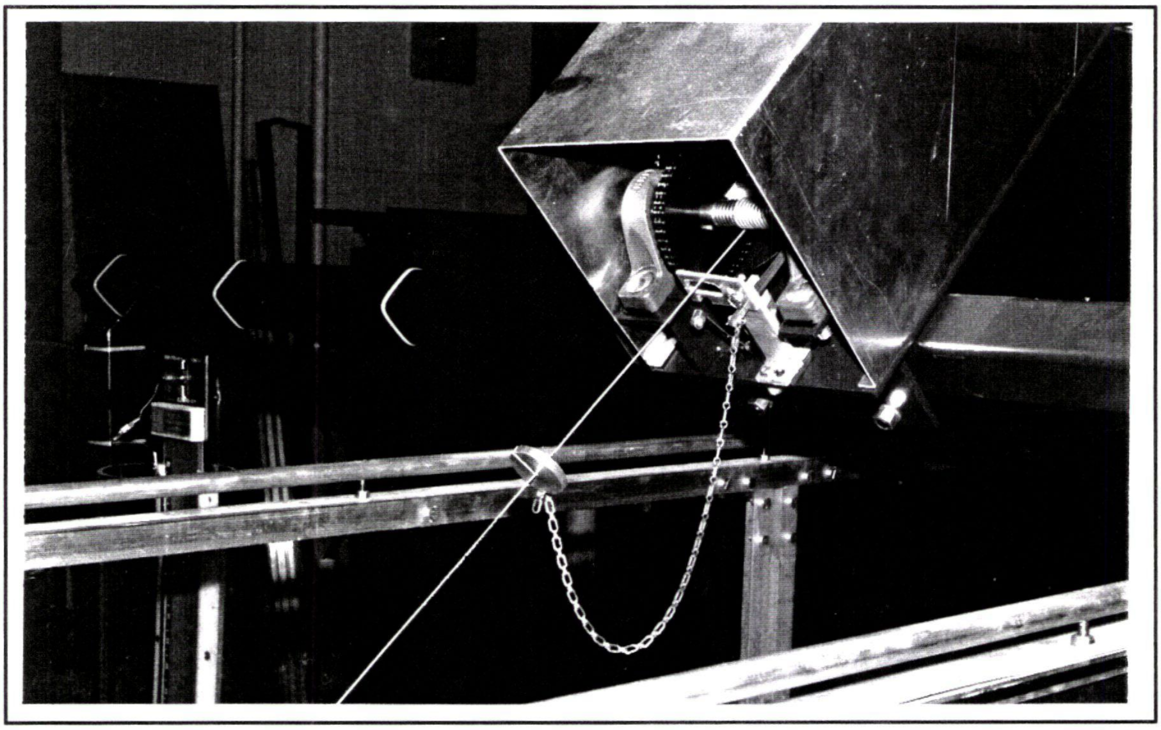


Plate 5.5 - Auto-stop mechanism on winch to prevent gate from being raised or lowered too far.

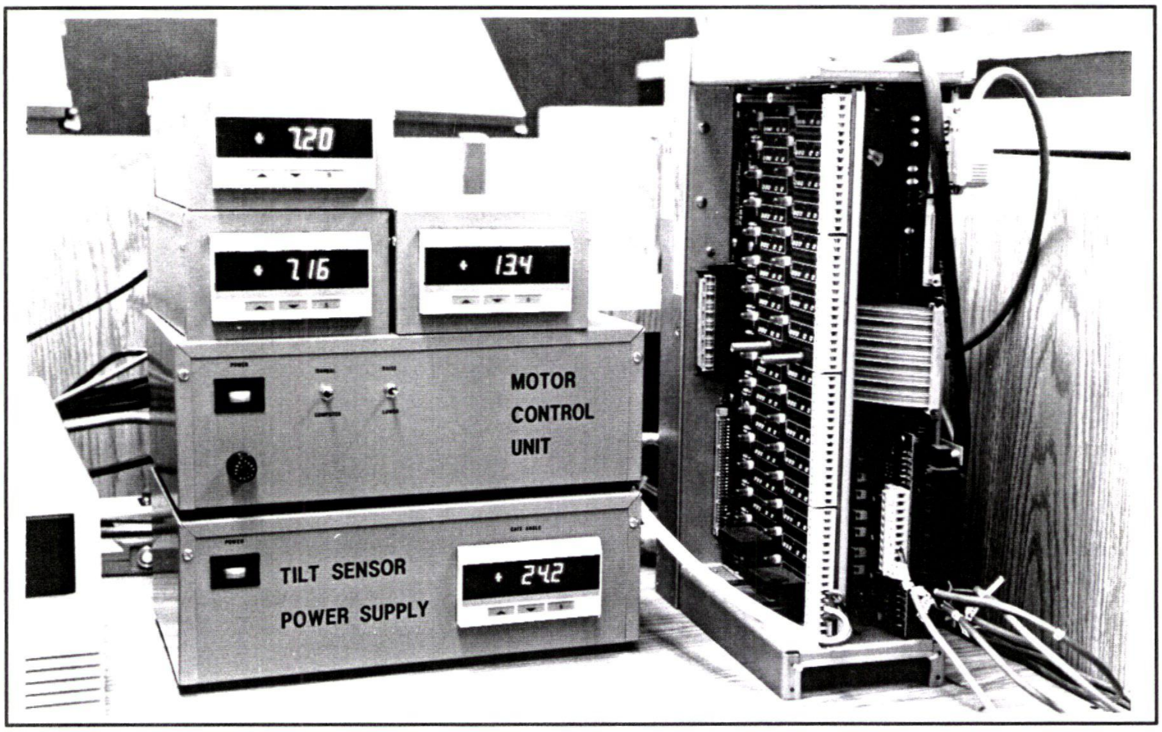


Plate 5.6 - Instrument gauges on left and MiniSAFE on right. Upper two gauges on left are for level indicators, upper gauge on right is for flow rate.

5.4 Level Indicators

Two water level indicators are installed at locations shown on Figure 5.1 and Plate 5.1. Each indicator consists of an electric sensing element free standing within a transparent plastic cylinder, as shown in Plate 5.7. The cylinder is hydraulically connected to the bottom of the flume by a flexible plastic hose (open at both ends), thus allowing water to rise in the cylinder to the height of water in the flume. This type of connection simulates a stilling well which dampens rapid fluctuations in the flume water level.

Each sensing element is connected to a Drexelbrook transmitter. As water rises in the cylinder the element senses a capacitance which varies linearly with the depth of water. This capacitance is normally translated to a current output by the transmitter. The university technical staff rewired the connections so that the transmitter would send a voltage output signal instead. This was necessary because the available metering equipment and controller are only able to receive voltage inputs.

5.5 Monitoring Equipment

Digitech digital panel meters provide output measurement readings of the water depth at both level indicators, the flow rate and the gate position. These are shown on Plate 5.6.

It was previously described in Section 5.4 that each level indicator

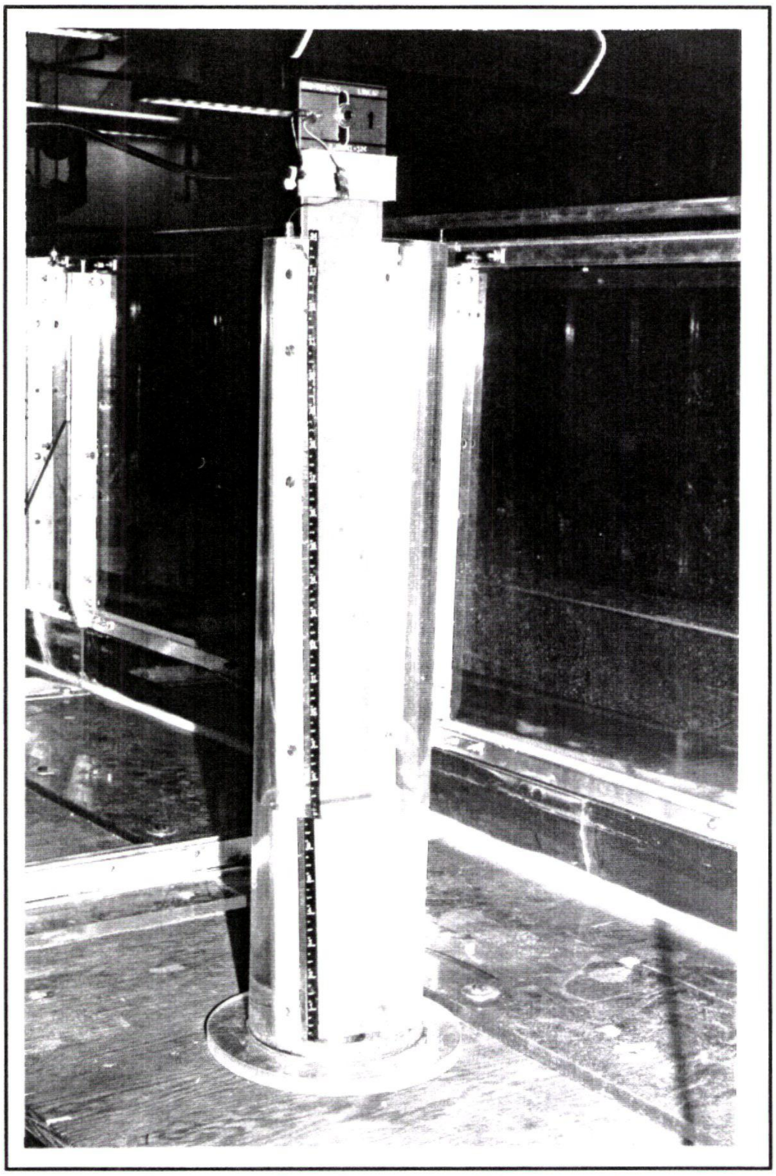


Plate 5.7 - Level Indicator #1

transmitter emits a voltage output which corresponds to a unique depth of water. The two panel meters connected to the level indicators were calibrated to translate the corresponding voltages to depths of water in inches, with a corresponding voltage output to the controller (Section 5.6).

A panel meter is connected to a flowmeter on the main water supply pipe, for remote readout of the discharge. The meter is calibrated to display the flow rate in litres/sec. (l/s).

The fourth panel meter provides remote readout of the gate position in units of degrees vertical relative to horizontal position. This is made possible by a Penny & Giles tilt sensor which is mounted on the downstream side of the pivoting gate (aluminum plate), shown on Plate 5.8. This photograph shows a metal shroud around the tilt sensor which protects the unit from water. The sensor is hidden from view, but it is partly visible in Plate 5.2.

A wiring diagram of the tilt sensor is included in Appendix B.

5.6 Controller

The controller used for the project is an advanced programmable controller called MiniSAFE, manufactured by Control Microsystems. Detailed documentation is available from either the manufacturer or Department of Civil Engineering which purchased the unit. This section will highlight the key elements of the controller and its application in this project.

The MiniSAFE unit is shown in Plates 5.6 and 5.9., the latter showing the total work station. The MiniSAFE can execute control functions in two ways. First, it has control blocks which can be programmed to execute a variety of control functions, including P, PI, PD or PID. There are sixty-

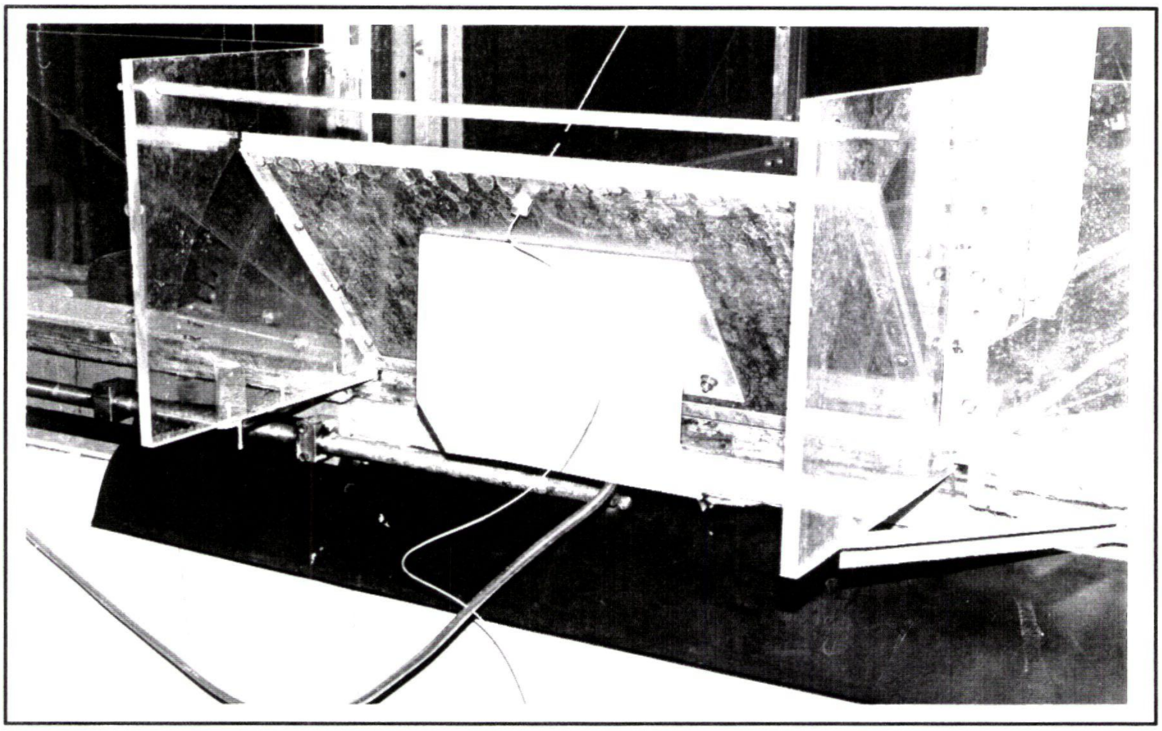


Plate 5.8 - Tilt sensor mounted on underside of gate. Only the protective shroud is visible.

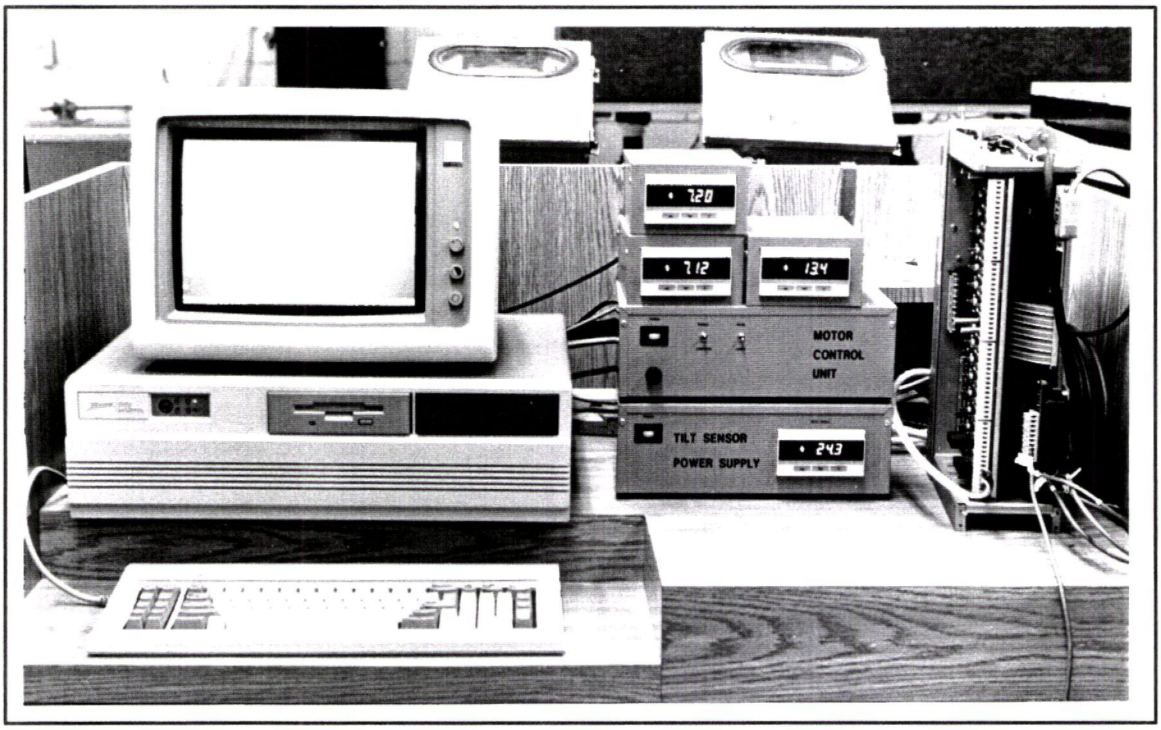


Plate 5.9 - Work station with host computer on left, gauges in centre and MiniSAFE on right.

four (64) control blocks that can be programmed separately or in combination with each other, thus making the MiniSAFE a powerful hardware tool for complex control applications.

Second, the MiniSAFE has a built-in programming language called SAFE BASIC which can be used to write simple control programs to carry out specific control functions, or execute a variety of tasks together with the control blocks. SAFE BASIC is a BASIC language program with fewer commands than available with BASIC, and newer ones designed specifically for control purposes. Once a program is created, with or without control blocks, it is saved and executed directly by the controller.

Like any controller, the MiniSAFE has input and output channels to receive data and send output signals. The MiniSafe has 16 analog input channels and 4 analog output channels. It also has 4 digital channels which can be used for either input or output, each channel comprising 8 bits. Outputs from the panel meters for the level indicators, tiltmeter and flow meter are analog signals. They are connected to the MiniSAFE's analog input channels 1, 2, 3 and 4 respectively. The only output signals occur to the gate motor (winch) and relay switch, which are all digital control. These outputs are connected to the MiniSAFE's digital channel 4, bits 2 and 1 respectively. Also, the butterfly valve is connected to analog output channel 16 so that the valve position can be controlled by the MiniSAFE. However, this feature was not used in the experiments.

5.7 Host Computer and Software

In order to program the controller, initiate operations and retrieve data it is necessary to link it with a host computer. The laboratory computer was used in this case. It is an IBM Compatible 286 PC, shown in Plate 5.9. The software program PROCOMM PLUS, by Datastorm Technologies Inc., provided the communication link between the computer and the MiniSAFE.

During program execution throughout the lab experiments, the communication link between the host computer and MiniSAFE was maintained. Input data collected by the MiniSAFE was downloaded onto a $3^{1}/_{2}$" floppy diskette in the computer's disk drive, as an ASCII file. Later, this file data was processed for graphical analysis using The QUATTRO PRO software program by Boreland, Version 3.0. The plotted data in Chapter 7.0 was created using this software.

CHAPTER 6.0

PROGRAM DEVELOPMENT

Early attempts at developing a control program using the MiniSAFE control blocks were largely unsuccessful. For unexplainable reasons the gate was not responding to the control block algorithm, whereas it would respond to direct SAFE BASIC commands. It was suggested by some of the University technical staff that the wiring and hardware used may be inappropriate for the control block outputs. This could be confirmed by testing and monitoring data from the control block outputs. However, it was decided to not pursue this option, but rather to develop a control program using only SAFE BASIC commands. Two factors led to this course:

1. The control algorithm required is fairly straight forward and simple to develop using SAFE BASIC;
2. It had already been proven that gate response could be achieved by direct SAFE BASIC commands.

The following describes the development of SAFE BASIC programming for this project, and various improvements made throughout the laboratory work. Appendix A includes key programs used. Copies of the programs on computer diskette are available from the author.

6.1 Calibration Studies

Each of the level indicators, flow meter and gate tilt sensor transmit a voltage output, between 10V and -10V, which represent values of depth, flow rate and gate setting. The analog input channels connected to receive this data return numeric values between the range of 4096 and -4096, which are proportional to the magnitude of voltage received. To use this data in the control algorithm, or otherwise for monitoring purposes, appropriate conversion relationships were derived to translate the input voltages (to the MiniSAFE) into meaningful unit values.

It was decided to match the units being read by the panel meters because they had already been calibrated by University staff, and it was desirable to retain consistency with these meters for the purpose of quickly spotting problems. During execution of the laboratory work, it was more convenient to monitor the meters than the converted output data being printed on the host computer screen. The appropriate units used were inches (in.) for water depth, litres/second (l/s) for flow rate and degrees (deg.) for gate setting.

The method used in calibrating the input data was to vary the corresponding water depth (Level Indicator #1), flow rate and gate settings throughout the full range of each, and record the panel meter display value against the analog input value for each setting. The data was plotted graphically, a linear relationship was interpolated and a mathematical equation was derived for each. These equations were then used in the SAFE BASIC programming to convert the input data to inches, litres/second and degrees respectively.

Figures 6.1 to 6.3 inclusive show the data graphically, and the following equations were derived:

$$Depth(in.) = \frac{AnalogIn}{204.6} \qquad [6.1]$$

$$Q(l/s) = 0.362(AnalogIn - 694) \qquad [6.2]$$

$$Gate(deg.) = \frac{AnalogIn - 702}{2.68} \qquad [6.3]$$

It was discovered that the MiniSAFE input data fluctuated slightly (approximately ± 2.5 %) due to minor disturbances in the voltages, particularly the gate position and flow rate. By comparison, the panel meters would filter out these fluctuations. This was another advantage to using the meters to monitor the laboratory work rather that the computer screen. These fluctuations were not significant enough to affect the work, but they made it difficult to pinpoint minor changes in data. The graphical results in Chapter 7.0 show this phenomenon, particularly the gate setting when it is at a constant position.

In addition to the above calibration, it was necessary to determine the rate of gate movement c, required for determination of Δt in Equation 4.10. This was done by manually activating the winch to move the gate through a range of angles and timing the duration using a stop-watch. Figure 6.4 is a plot of the results, from which a value of c=2.5 deg./sec. was selected for the control algorithm.

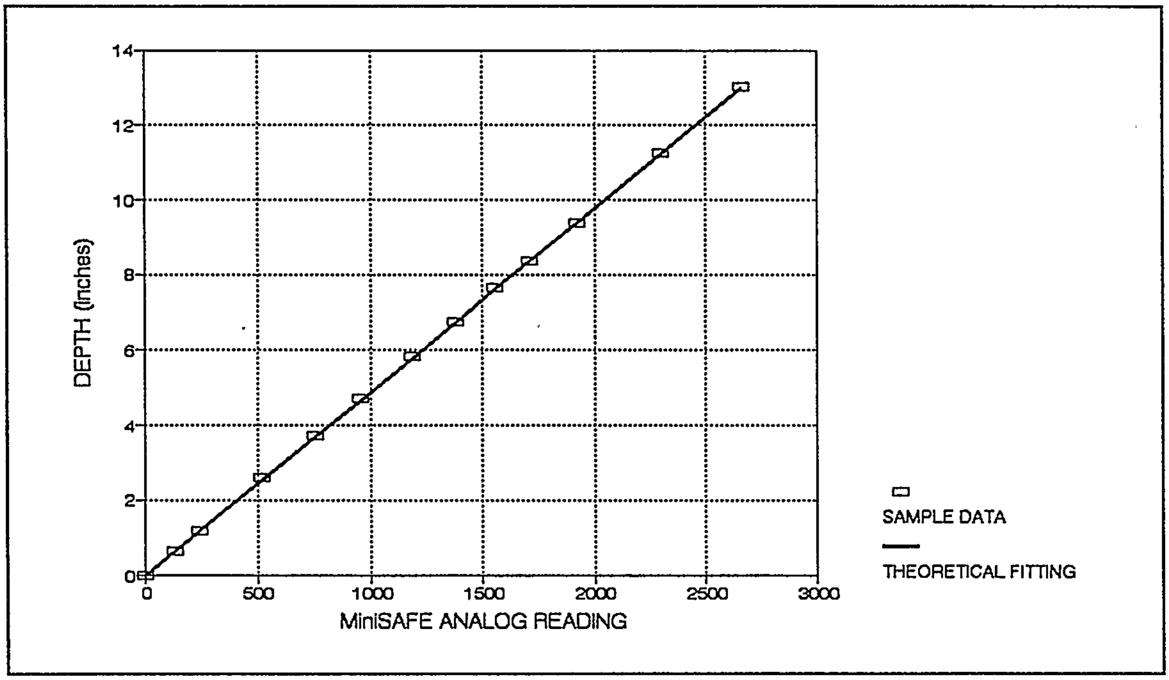


Figure 6.1 - Calibration of Water Depth

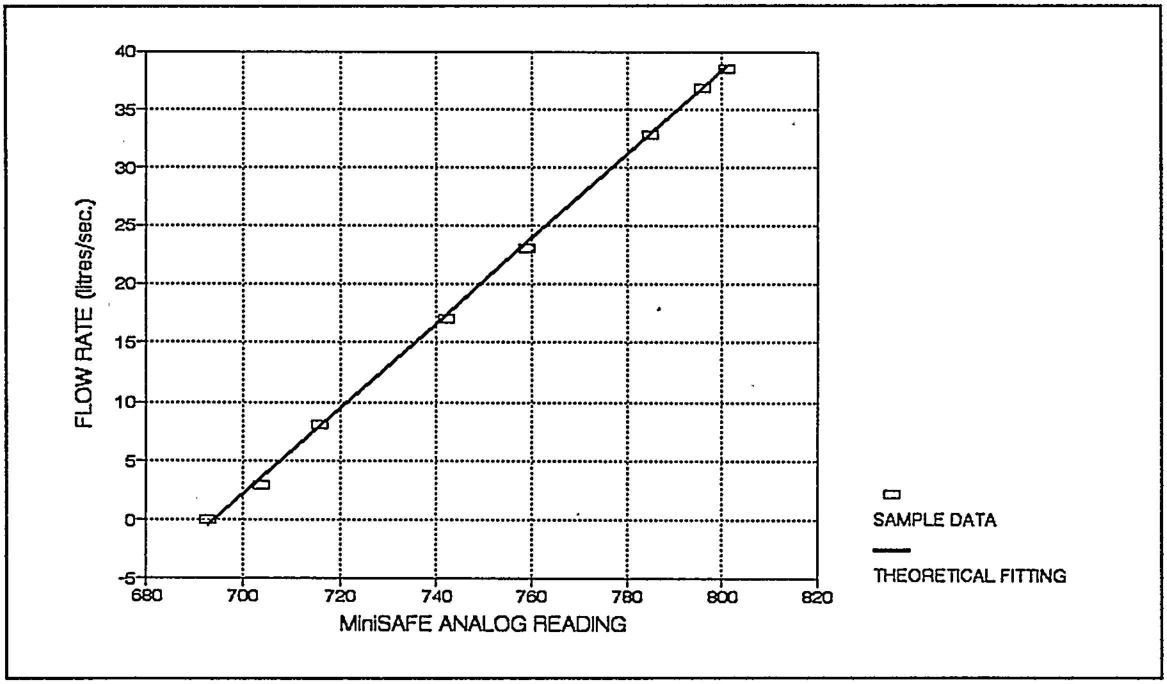


Figure 6.2 - Calibration of Flow Rate

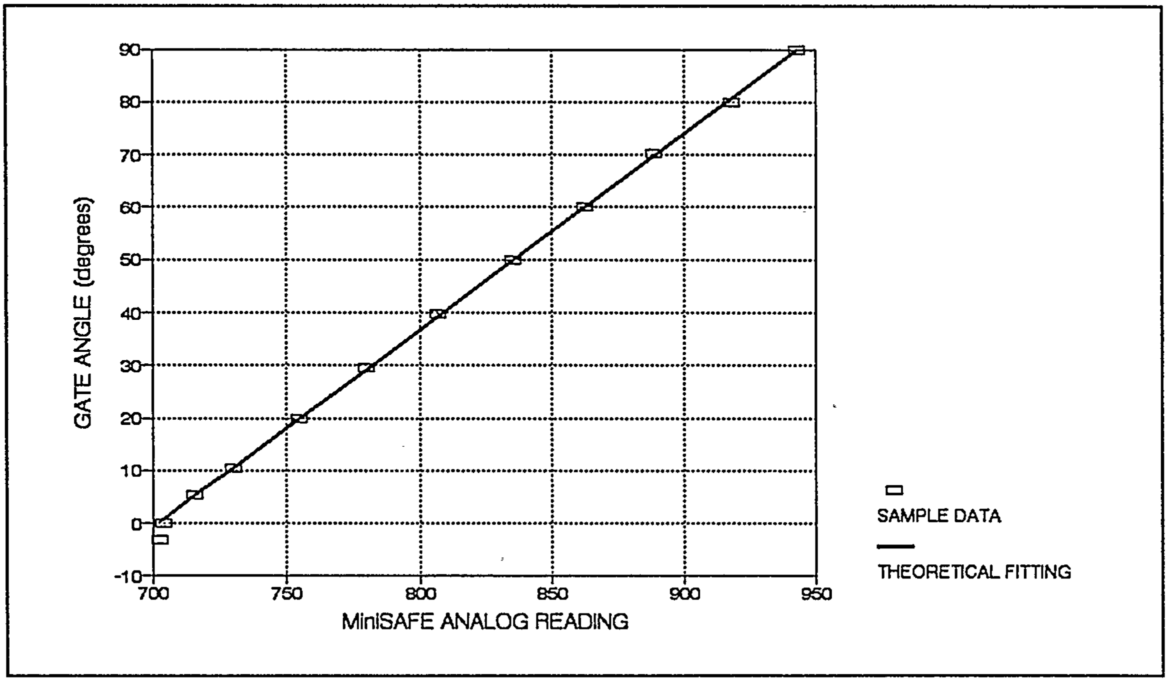


Figure 6.3 - Calibration of Gate Position

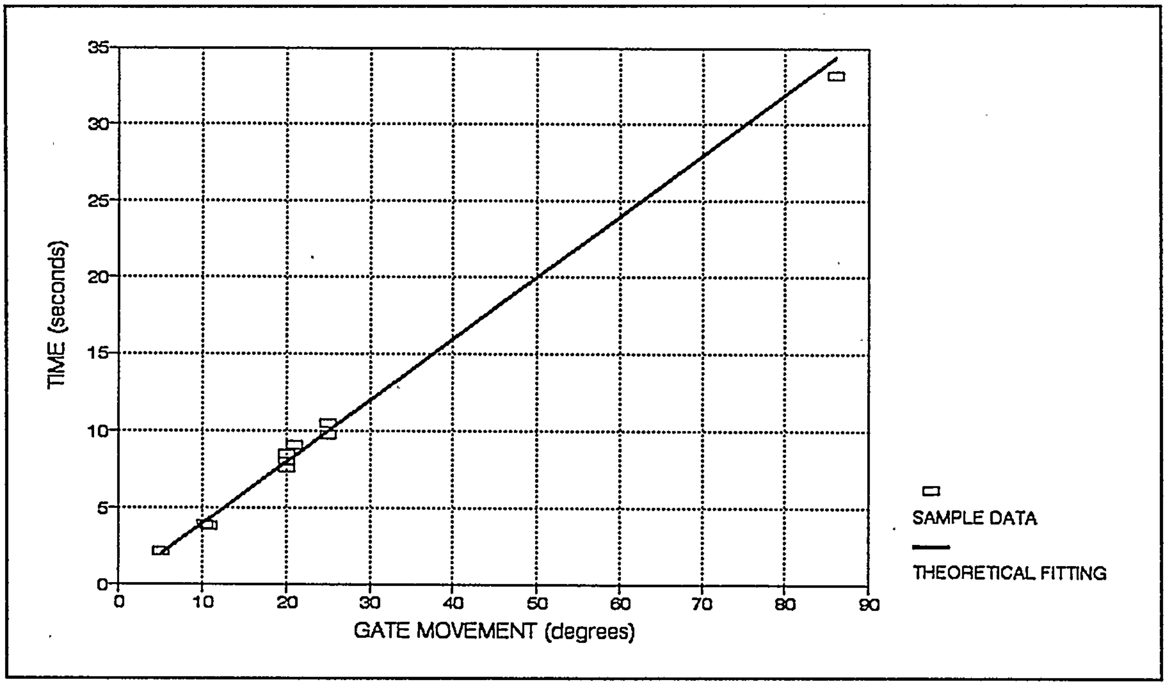


Figure 6.4 - Rate of Gate Movement

6.2 Basic Control

Basic Control refers to the fundamental commands and algorithm structure used to execute SOT/SRT Floating Control, discussed earlier in Chapter 4.0. The control program was executed for the duration of the gate operation unless interrupted by a "Control-Break" (Ctrl-Brk) from the keyboard.

The program was required to carry-out the following tasks:

- receive input data for operation settings and algorithm parameters
- determine the error between water level and set point
- compute the change in gate position, up or down
- compare the error to water depth deadband and determine if gate adjustment is necessary
- adjust the gate position (if required)
- return to start of algorithm

Other steps were added to supplement the above ones and provide data to the operator:

- print the water level, flow rate and gate position
- wait a period of time between successive gate adjustments
- warn operator if target water level is too high

Figure 6.5 is a schematic of the control program developed early in the project, and which formed the nucleus for future improvements. Most of the elements are self explanatory or were discussed previously, but three very key steps require further explanation; timer for power on, waiting time period and printing of analog input data.

SAFE BASIC includes commands to create a timer sequence which counts down to zero from a given time period, at intervals of 0.1 seconds. The first timer sequence is programmed to count down the value of Δt (Equation 4.10), which represents the time that gate adjustment is made. The second timer sequence counts down a waiting time period, input by the operator, which causes a time delay following each gate adjustment before the next algorithm is started. This corresponds to the Δt term in Equations 4.15 and 4.17.

It was recognized early in the program development that the waiting time is an important part of the control operation. If it is equal to zero the gate will continue to move up and down because the water level cannot respond fast enough due to channel storage affects. This will cause the water level to cycle about the set point, thus simulating Two-Position control. Adding a waiting time allows the water level to "catch up" in response to gate adjustments before the next algorithm (gate adjustment) is executed. A long waiting time will provide the smoothest response in water level, but it will also cause a long period of time to lapse until equilibrium about the target is achieved. In part, this waiting time simulates the anti-hunt action of the Little-Man (SOT/SRT) controller.

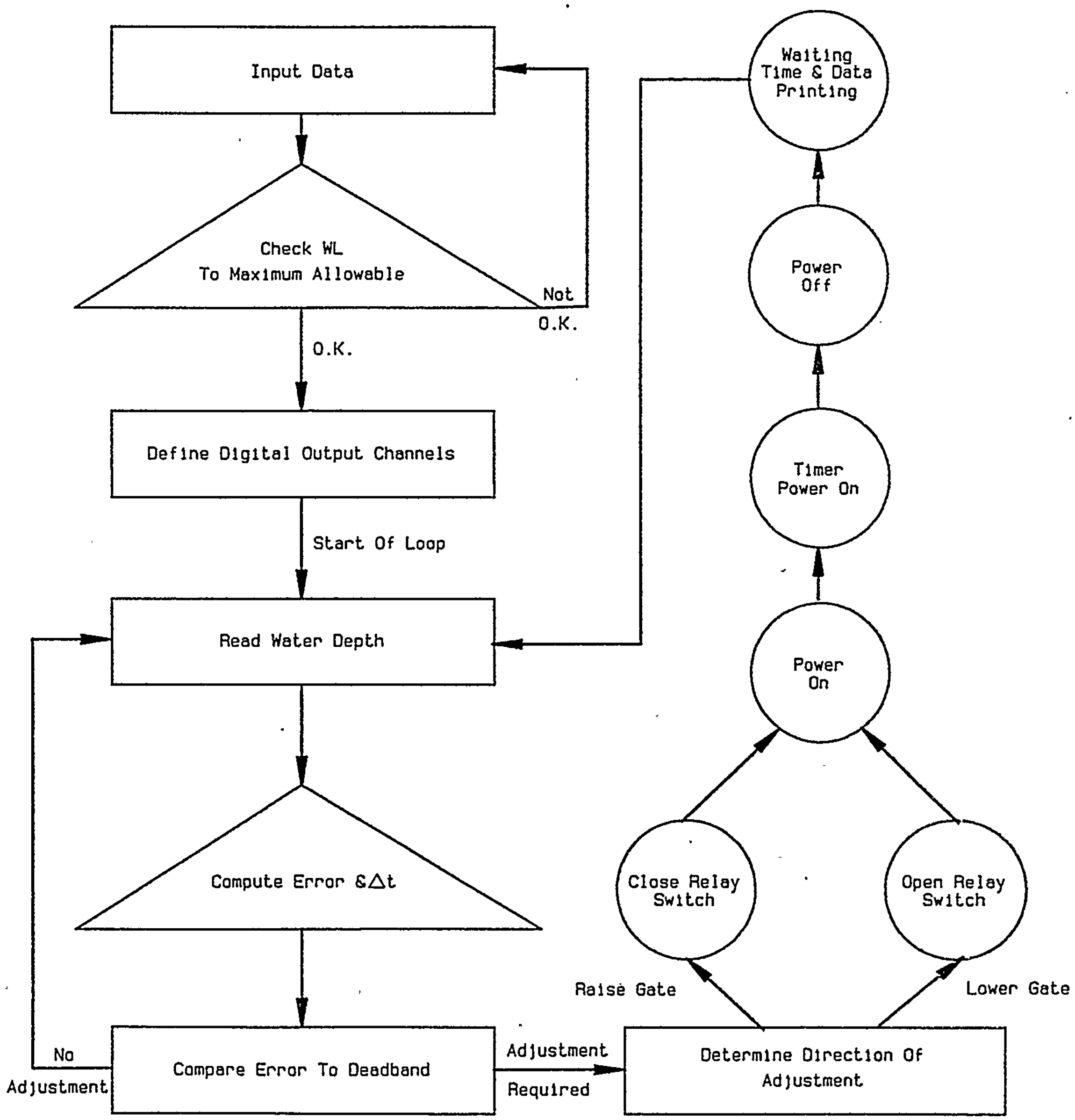


Figure 6.5 - Basic Control Program Structure

Printing the analog input data (water levels, flow rate, gate setting) was not a necessary element to the control algorithm, but it was absolutely essential to the analysis of the physical characteristics of this gate. It is not as important to visually study the data when scrolling up the screen as it is to send the data to a file for subsequent analysis. The control programs developed provided for printing of this data to the screen, while sending it to a file was accomplished by the PROCOMM PLUS software using a LOGIN command.

The earliest control program provided for the water level at Indicator #1 to be printed at the start of each loop and at the end of each gate adjustment. This gave only occasional points of data, and was improved in later programs by moving the second print command to the waiting time period and printing the data at one second intervals. Eventually, the print command at the start of loop was dropped, and the water level at Indicator #2, flow rate and gate setting were added to the remaining print command. This still left a gap in data during the gate adjustment timer sequence, but it was only significant during long gate movements which occurred infrequently. This data gap was ignored during subsequent analysis of the data.

The majority of project work was done with the control algorithm based on instantaneous readings of water depth at Level Indicator #1, referred to in the programs as Y1. A few gate operations were carried out with the algorithm based on the following variations:

- average of water depth readings during the waiting time period (1 sec. intervals) at Level Indicator #1,
- instantaneous water depth readings at Level Indicator #2,
- average of water depth readings during the waiting time period (1 sec. intervals) between Level Indicators #1 and #2.

6.3 PID Control

The program structure for PID control remained mostly intact from the basic control structure presented in the previous section. Figure 6.6 shows a schematic of the PID structure, and only minor differences are noted. The most notable change is the waiting time and printing of analog input data, which was moved to the start of the control loop as a cosmetic alteration.

Because the PID algorithm requires additional computations more input data was required, so an additional step was added; computation of total correction (Equation 4.17). By setting the Reset Time (RE) and/or Rate Gain (RA) equal to zero the control algorithm simulates P, PI or PD control. Also, the total correction was compared to the deadband rather than the error. In theory this is a fundamental difference in philosophy, but in practice it did not appear to be a significant one. This is discussed further in Chapter 7.0.

One improvement was made that is noteworthy; regarding the waiting time and printing of analog input data (to the MiniSAFE). For a variety of

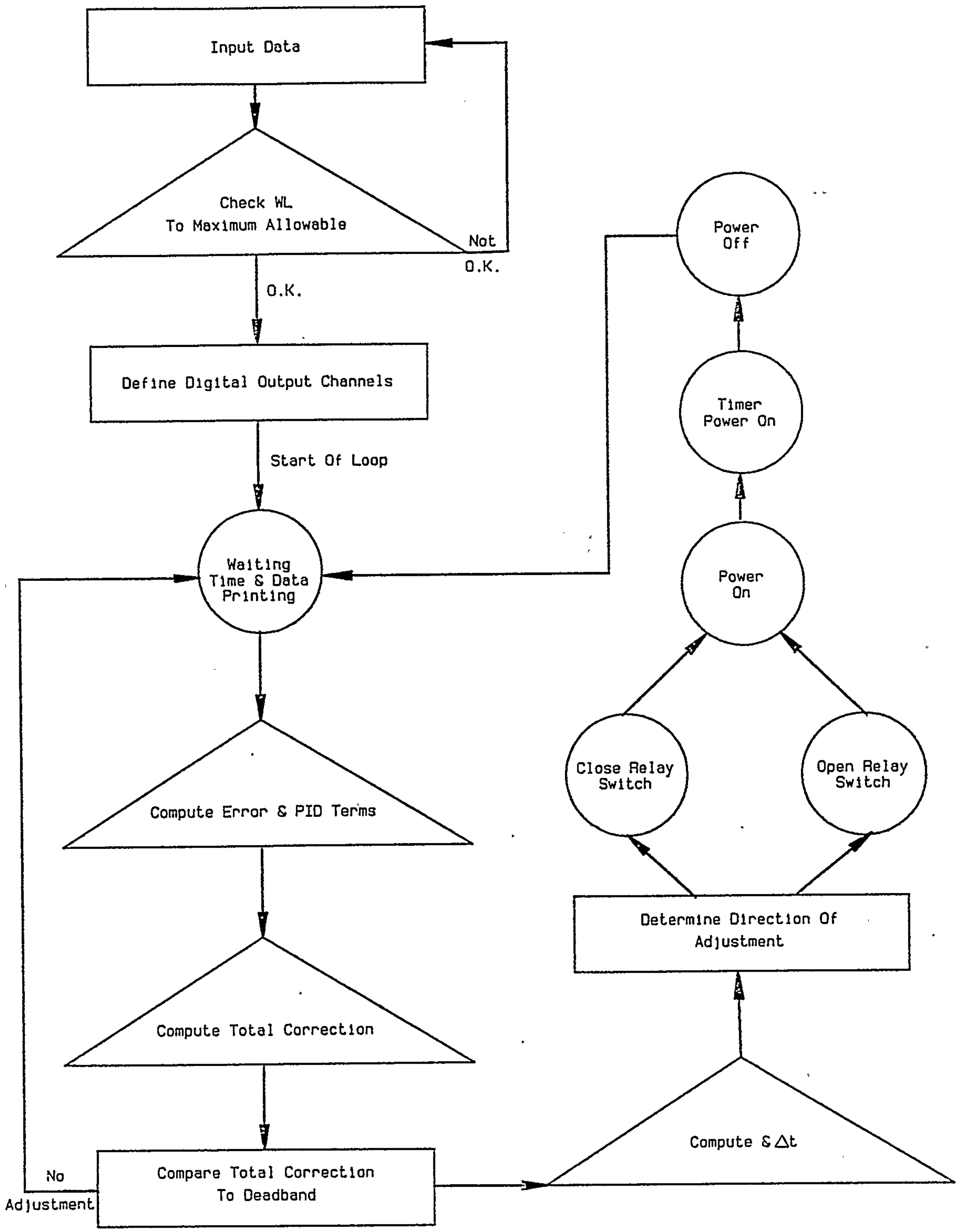


Figure 6.6 - PID Control Program Structure

reasons it may not be necessary to print the analog input data every second. Provision was made to specify the interval desired for printing the data, providing it is to a whole second and results in a whole number of data increments within the waiting time period. Also, to overcome the time gap associated with the gate adjustment timer sequence, a counter was included to keep track of the waiting and gate adjustment times throughout the program execution. For every set of analog input data that was printed, the running time was also printed. This meant that the data would be accurately represented in time. This counting did not allow for the normal running time of commands, but the program is so small that this time is non measurable.

A safety feature was added to prevent excessive corrections resulting from the PID algorithm, caused by a proportional gain too high, a reset time too low, a rate gain (absolute value) too high, or any combination thereof. The typical response would be for the gate to be raised past 90° or lowered past 0° in a cycling situation. If the total correction resulted in an adjusted gate position past these extremes, the program terminated without actual gate adjustment being implemented. The operator was then prompted to modify the PID parameters accordingly.

CHAPTER 7.0

CASE STUDIES

A total of two hundred and twenty two (222) gate simulations were conducted to test the physical characteristics of the pivoting gate while under Floating (SOT/SRT), P, PI, PD and PID control. Most of the testing was done by changing the target water level, referred to as set point change. The water would be allowed to stabilize at arbitrary levels, and the control programs would be run to raise or lower the levels to new targets. The programs would be terminated when equilibrium was reached or when it became clear that instability would result using the parameters given. The run times typically varied between 2 and 4 minutes, although an end time was not assigned.

The set point change condition was chosen because it would result in the most dramatic change in operating conditions. Initially, both set point increase and set point decrease situations were tested. It became apparent that the gate and upstream water levels responded similar to these changes for identical parameters, so set point decrease conditions were terminated to reduce lab time.

A few case studies were conducted in which the flow rate was varied, sometimes rapidly and sometimes gradually, while the set point remained unchanged. This was done using parameters that yielded optimum results under the set point change conditions. Case studies for these situations ran a little longer; generally around 5 minutes.

For all cases, only a water level deadband was used or considered. In historic situations, gate adjustment deadband was also incorporated into the control algorithm (Buyalski, 1977).

Details and results of the testing follows. Throughout the discussion "target" water level and "set point" will be used interchangeably, which are intended to hold the same meaning.

7.1 SOT/SRT Floating Control

Table 7.1 summarizes the parameters and operating conditions tested. Except as otherwise noted, the algorithm for all cases is based on depth readings at Level Indicator #1. The following nomenclature is used:

Valve = Valve setting for flow rate, between 0.0 (zero flow) and 10.0 (100% capacity)

WL = Target water level, or set point

ΔSP = Change ($\pm$) in set point

DB = Deadband

TW = Waiting time

Figures 7.1 to 7.19 are the plotted results of some key cases tested using Floating Control. The majority of set point decrease situations are not shown.

It was observed that while the results of a set point decrease are similar

Table 7.1 - Summary of Case Studies for Floating Control

Case No.	Valve	TW (sec.)	ΔSP (in.)	DB (in.)
1, 2	5.0	5	2	0.1
3, 4	5.0	10	2	0.1
5, 6A	5.0	20	2	0.1
6B, 7	5.0	5	5	0.1
8, 9	5.0	10	5	0.1
10, 11	5.0	20	5	0.1
12, 13	5.0	60	5	0.1
14, 15	3.0	5	5	0.1
16, 17	3.0	10	5	0.1
18, 19	3.0	20	5	0.1
20	varies	5	0	0.1
21	varies	20	0	0.1
22	varies	10	0	0.1
23, 24 [(1)]	3.0	10	2	0.1
25, 26 [(1)]	3.0	20	2	0.1
27, 28 [(1)]	3.0	30	2	0.1
29, 30 [(2)]	3.0	10	2	0.1
31, 32 [(2)]	3.0	20	2	0.1
33, 34 [(2)]	3.0	30	2	0.1
35, 36 [(3)]	3.0	10	2	0.1
37, 38 [(3)]	3.0	20	2	0.1
39, 40 [(3)]	3.0	30	2	0.1

(1) Algorithm based on average of depth readings at Level Indicator #1
(2) Algorithm based on single depth reading at Level Indicator #2
(3) Algorithm based on average of depth readings between Level Indicators #1 and #2

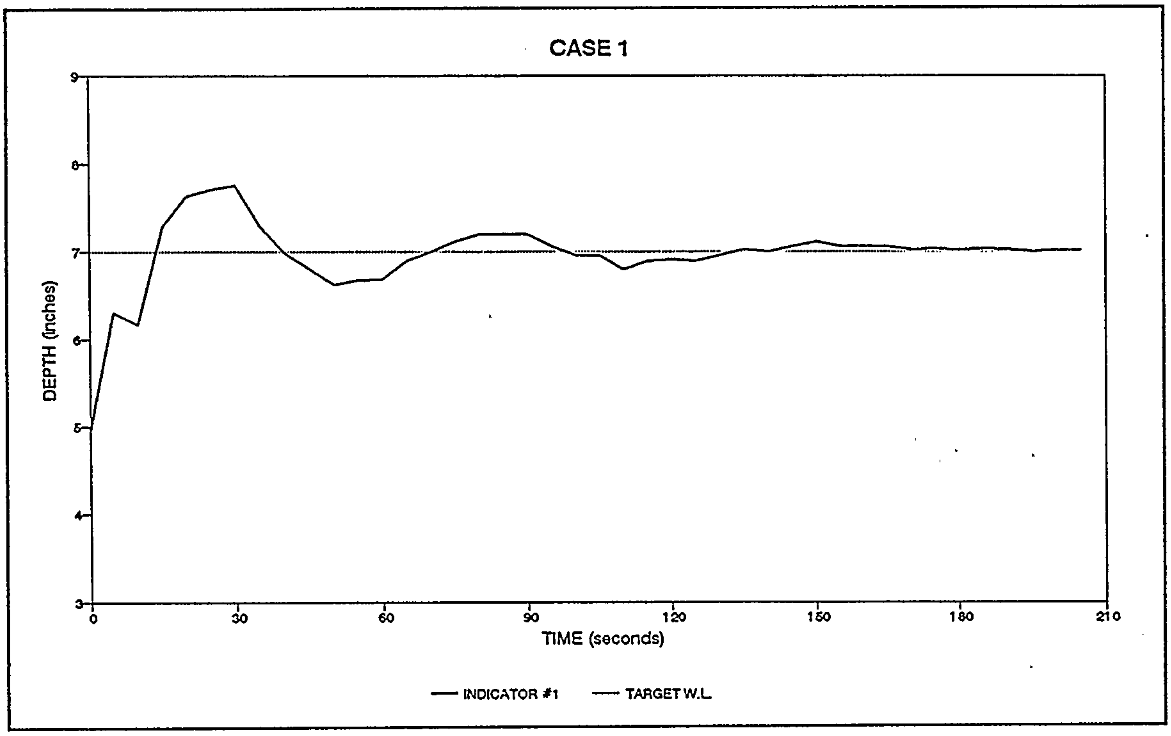


Figure 7.1 - Floating Control, CASE 1
Valve @ 5.0; TW=5 sec.; ΔSP=2 in.; DB=0.1 in.

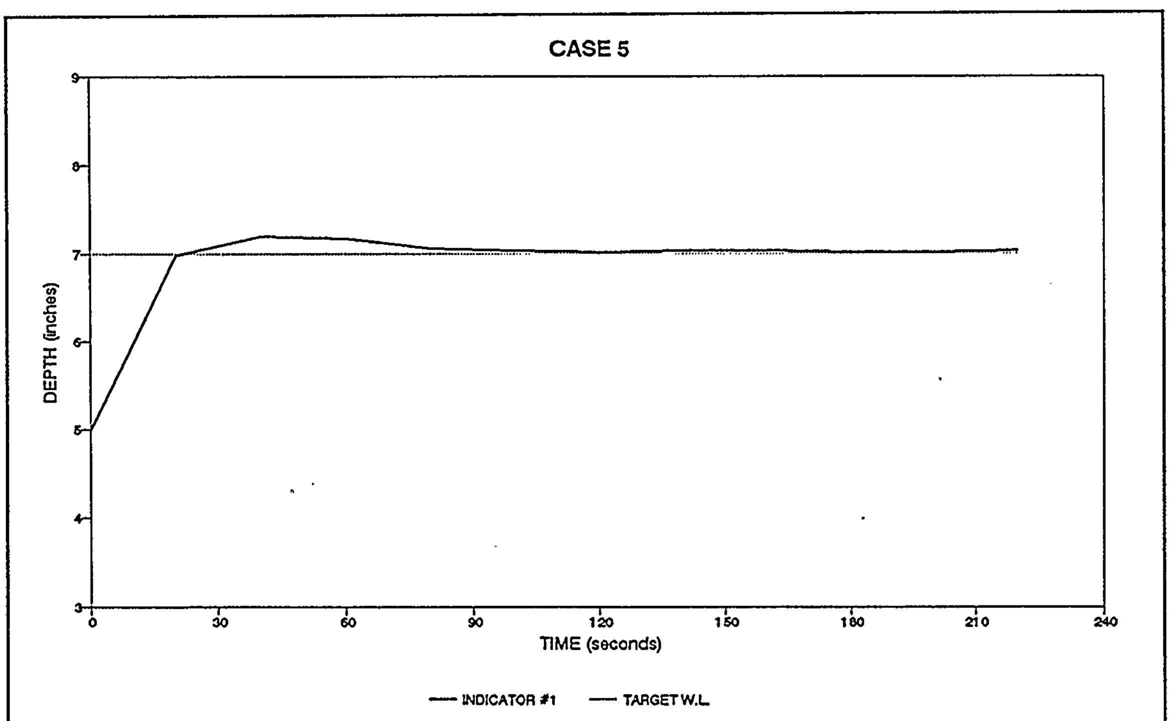


Figure 7.2 - Floating Control; CASE 5
Valve @ 5.0; TW=20 sec.; ΔSP=2 in.; DB=0.1 in.

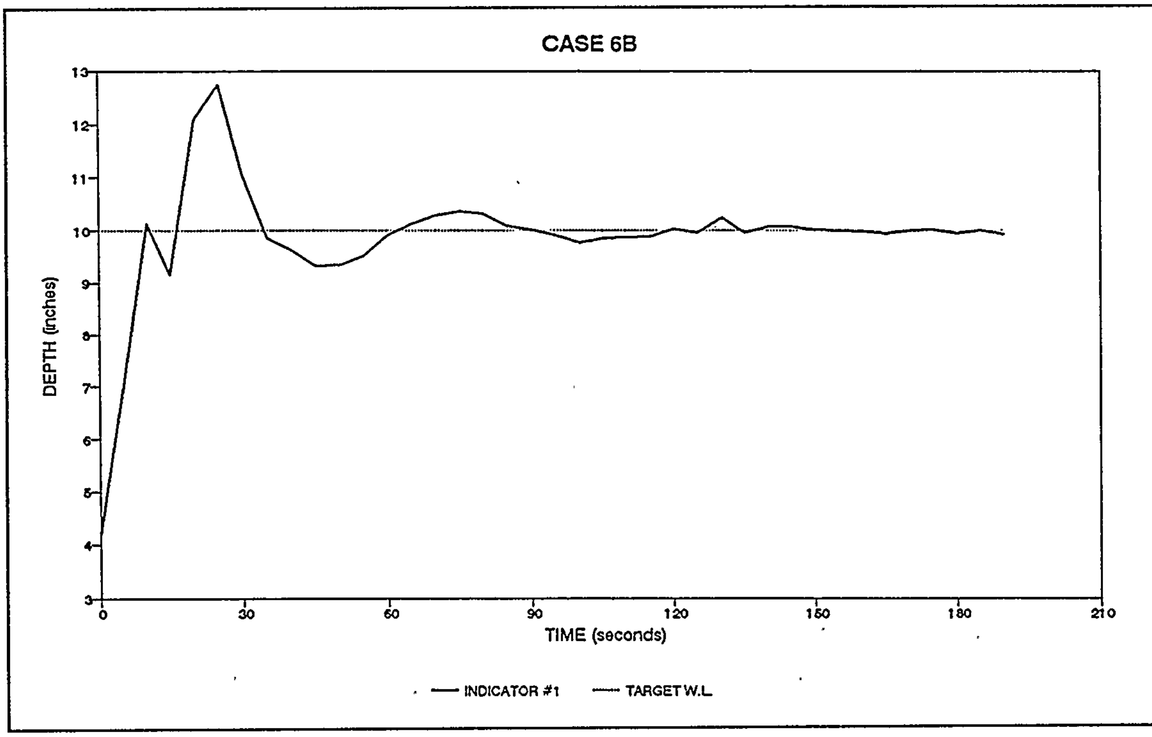


Figure 7.3 - Floating Control, CASE 6B
Valve @ 5.0; TW=5 sec.; ΔSP=5 in.; DB=0.1 in.

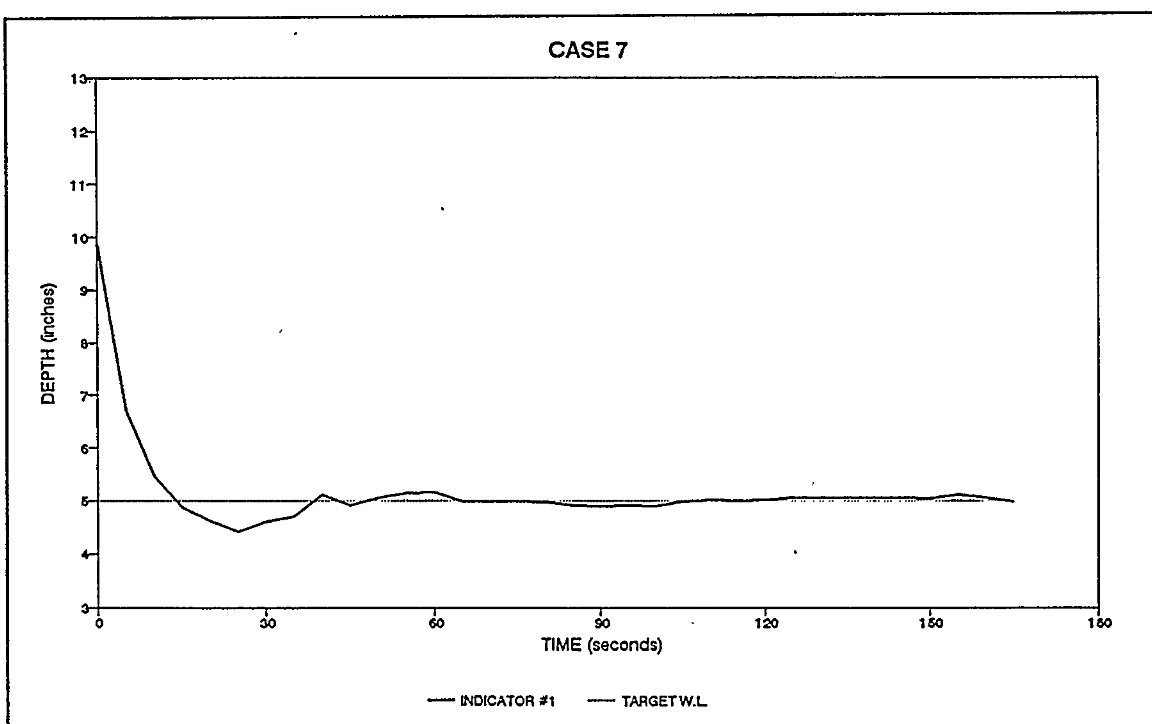


Figure 7.4 - Floating Control, CASE 7
Valve @ 5.0; TW=5 sec.; ΔSP=5 in.; DB=0.1 in.

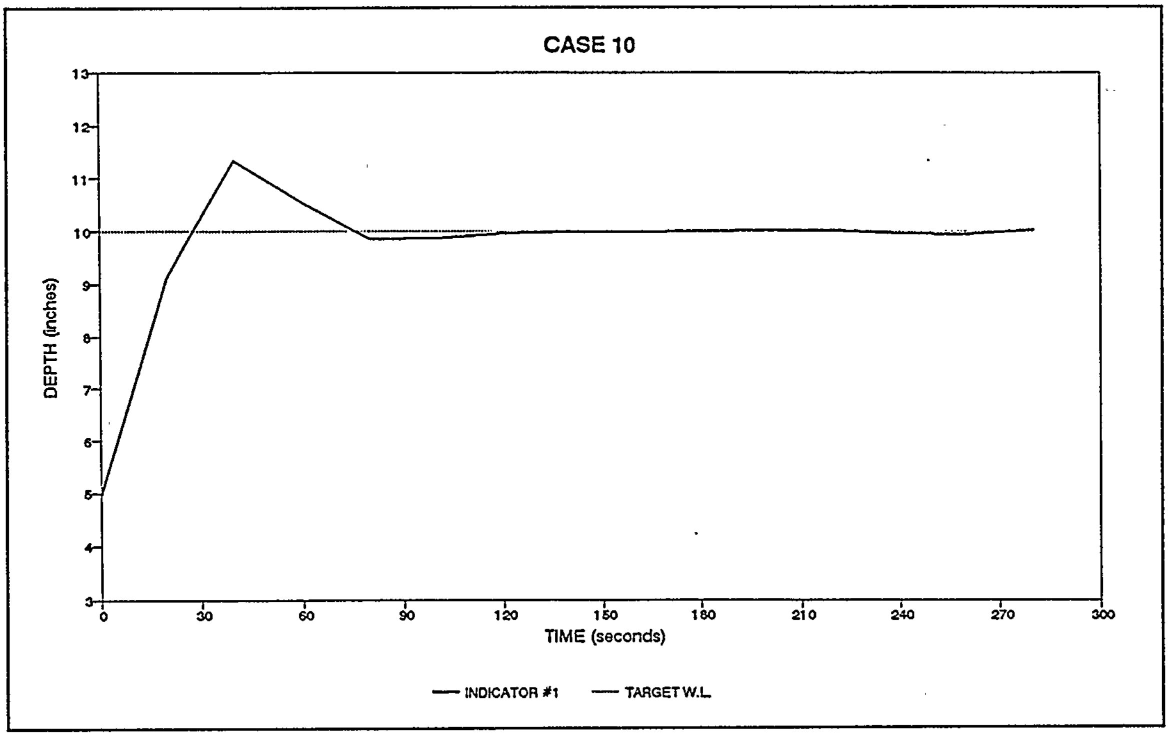


Figure 7.5 - Floating Control, CASE 10
Valve @ 5.0; TW=20 sec.; ΔSP=5 in.; DB=0.1 in.

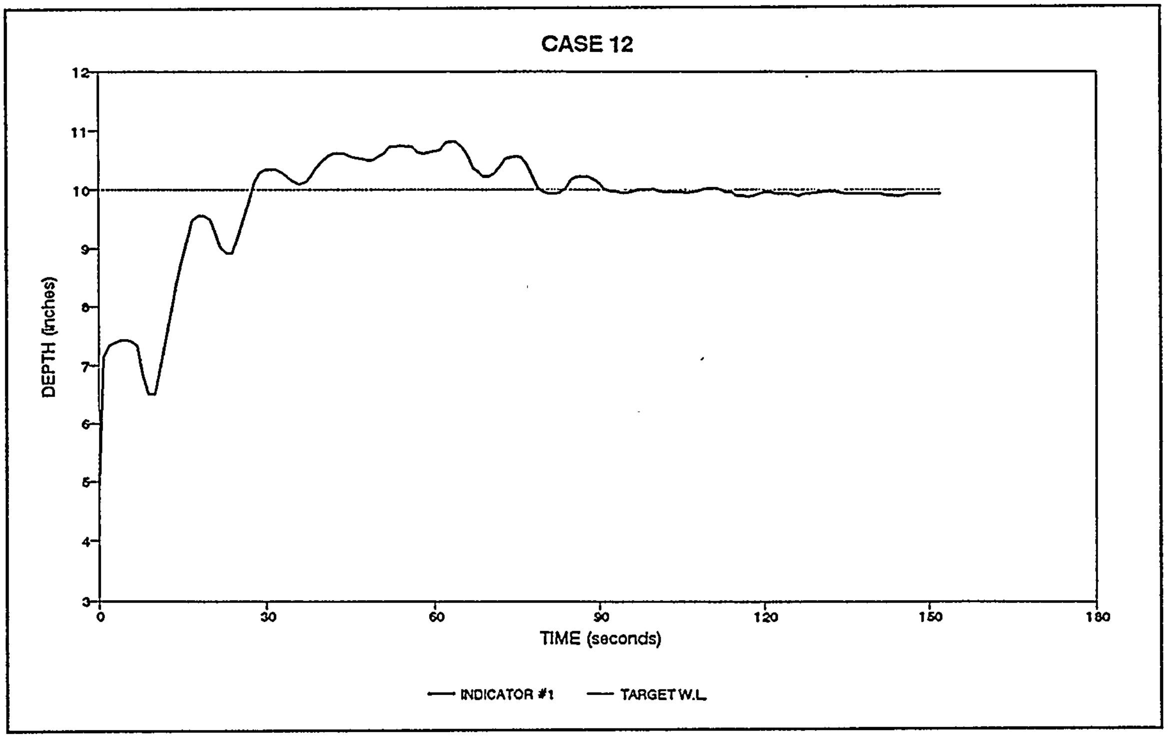


Figure 7.6 - Floating Control, CASE 12
Valve @ 5.0; TW=60 sec.; ΔSP=5 in.; DB=0.1 in.

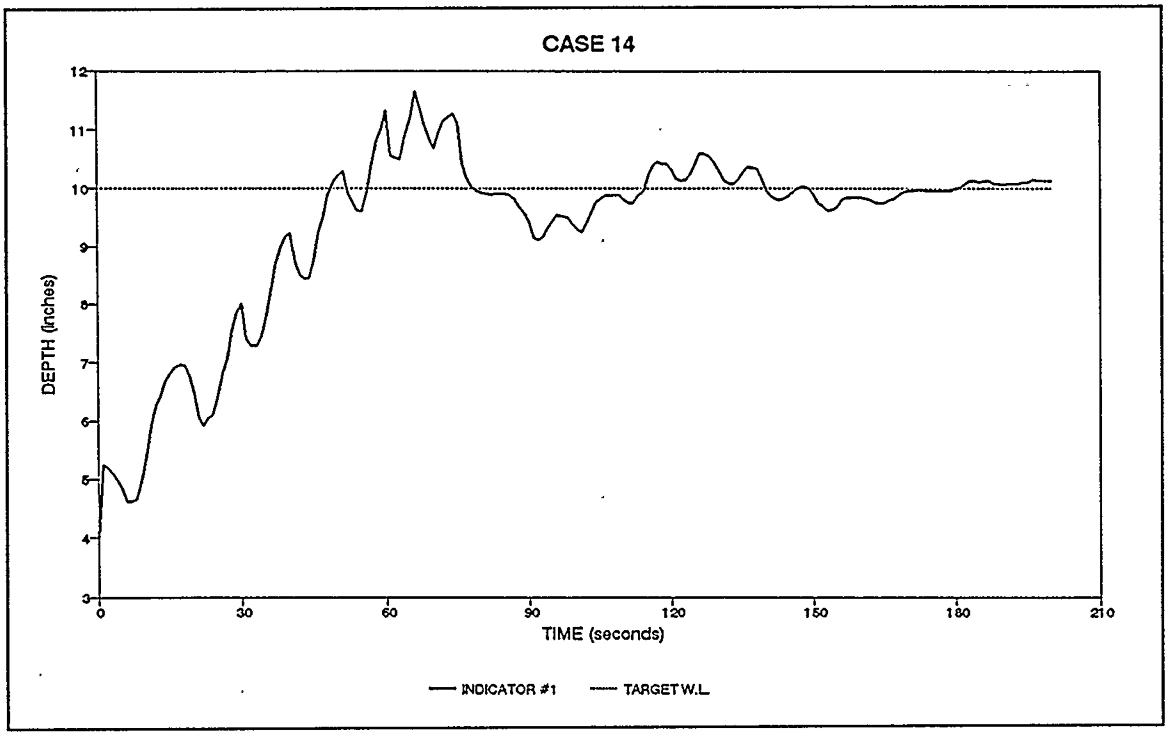


Figure 7.7 - Floating Control, CASE 14
Valve @ 3.0; TW=5 sec.; ΔSP=5 in.; DB=0.1 in.

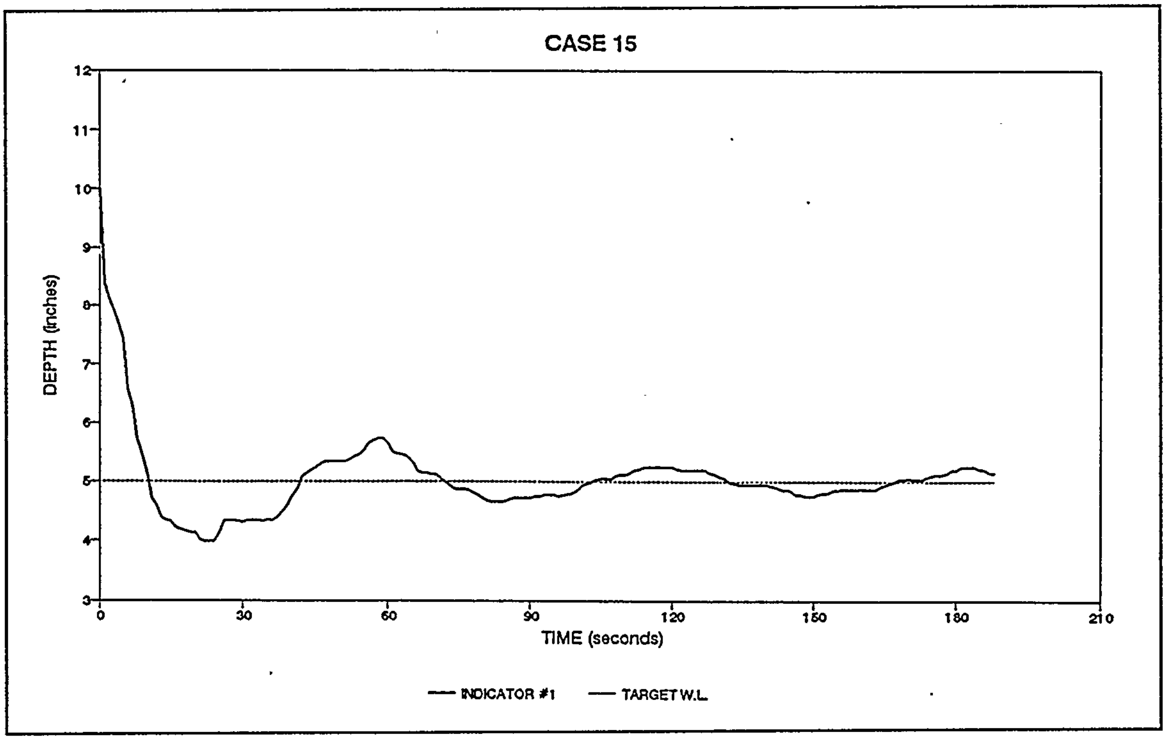


Figure 7.8 - Floating Control, CASE 15
Valve @ 3.0; TW=5 sec.; ΔSP=5 in.; DB=0.1 in.

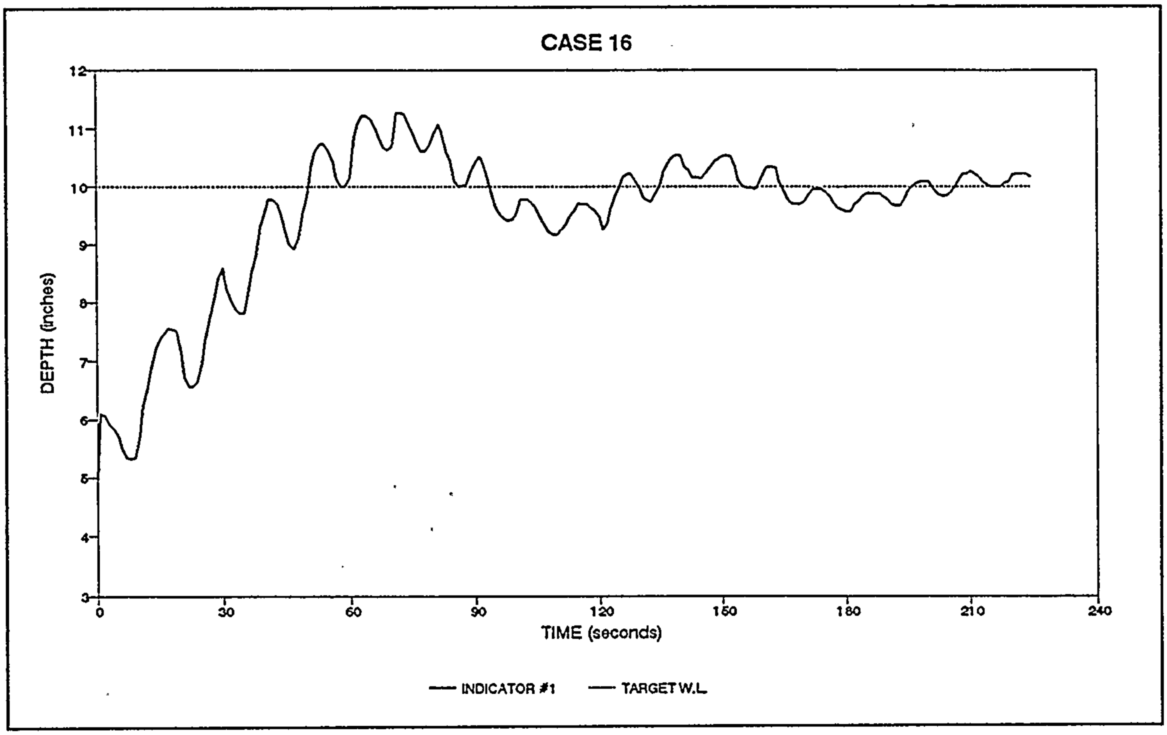


Figure 7.9 - Floating Control, CASE 16
Valve @ 3.0; TW=10 sec.; ΔSP=5 in.; DB=0.1 in.

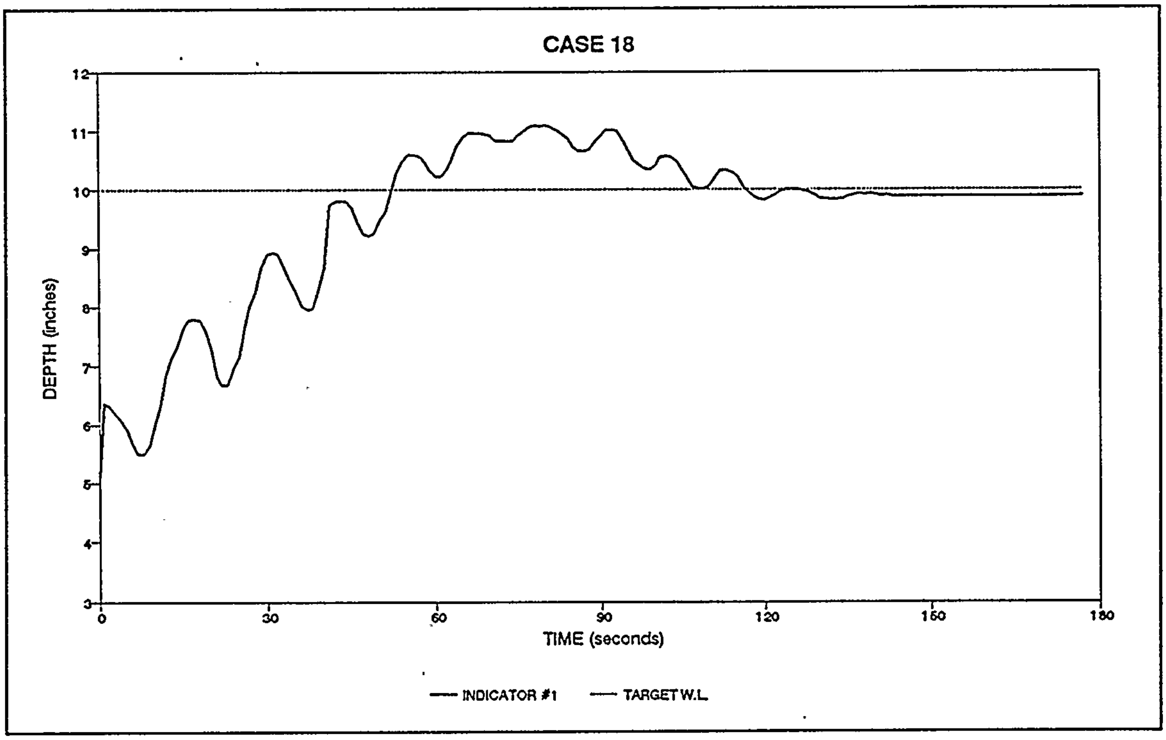


Figure 7.10 - Floating Control, CASE 18
Valve @ 3.0; TW=20 sec.; ΔSP=5 in.; DB=0.1 in.

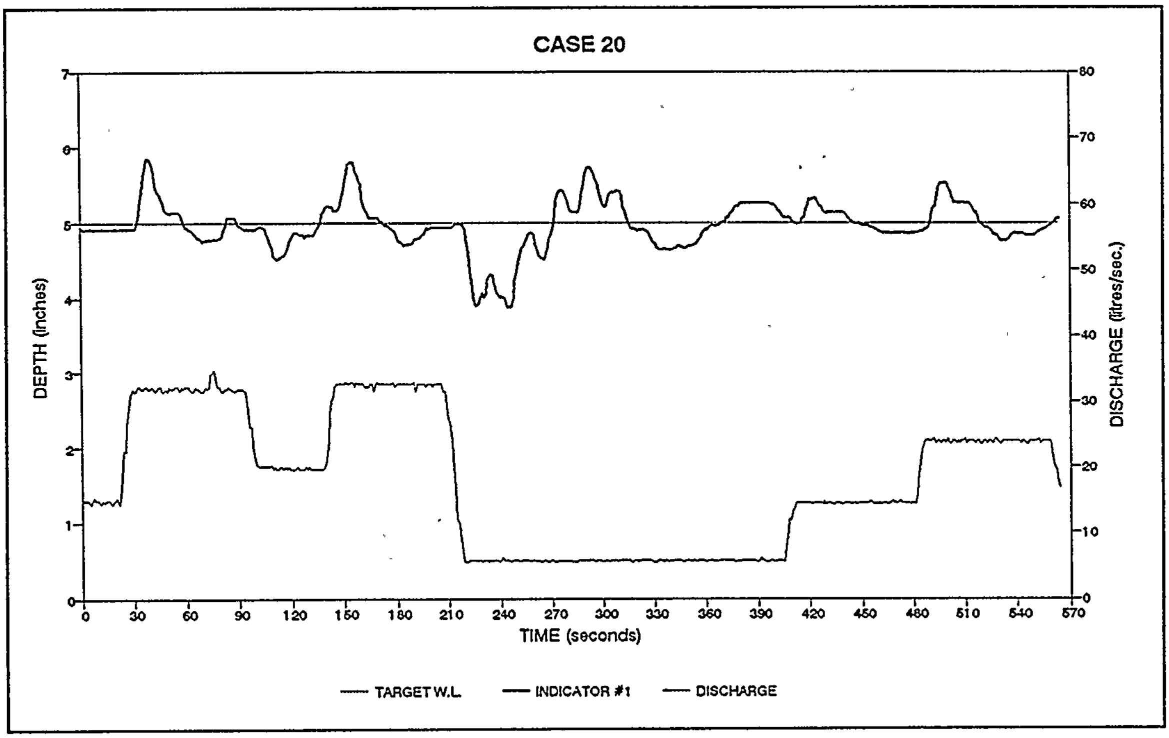


Figure 7.11 - Floating Control, CASE 20
Q varies; TW=5 sec.; DB=0.1 in.

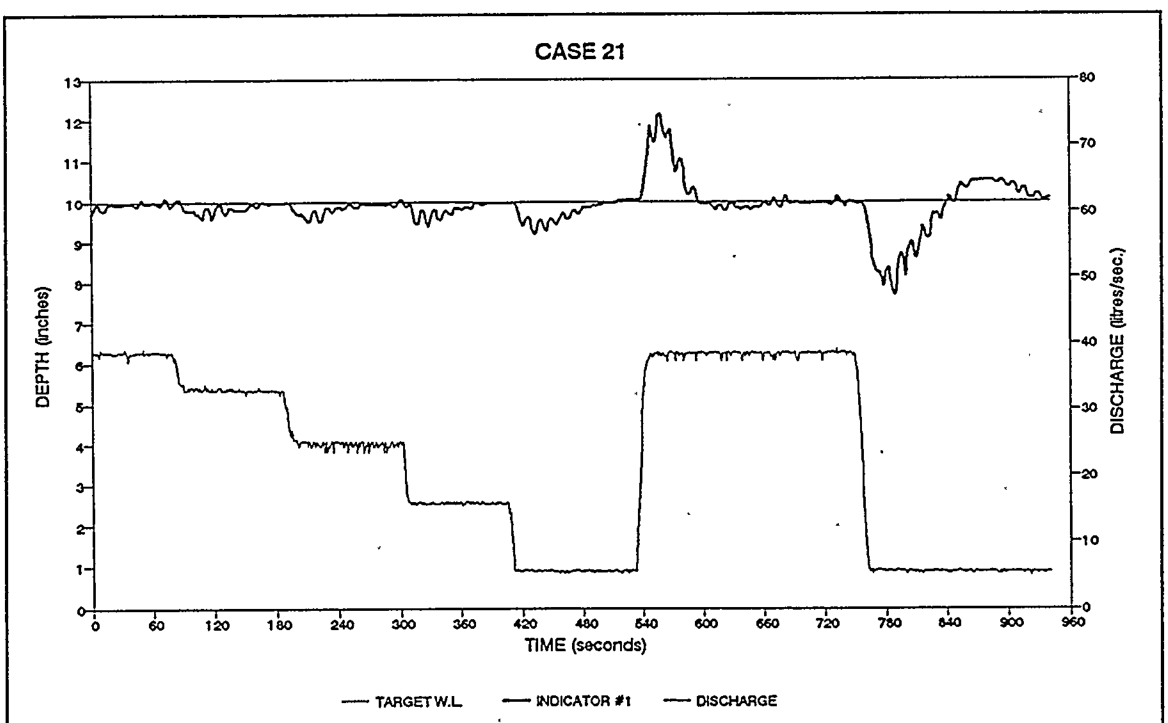


Figure 7.12 - Floating Control, CASE 21
Q varies; TW=20 sec.; DB=0.1 in.

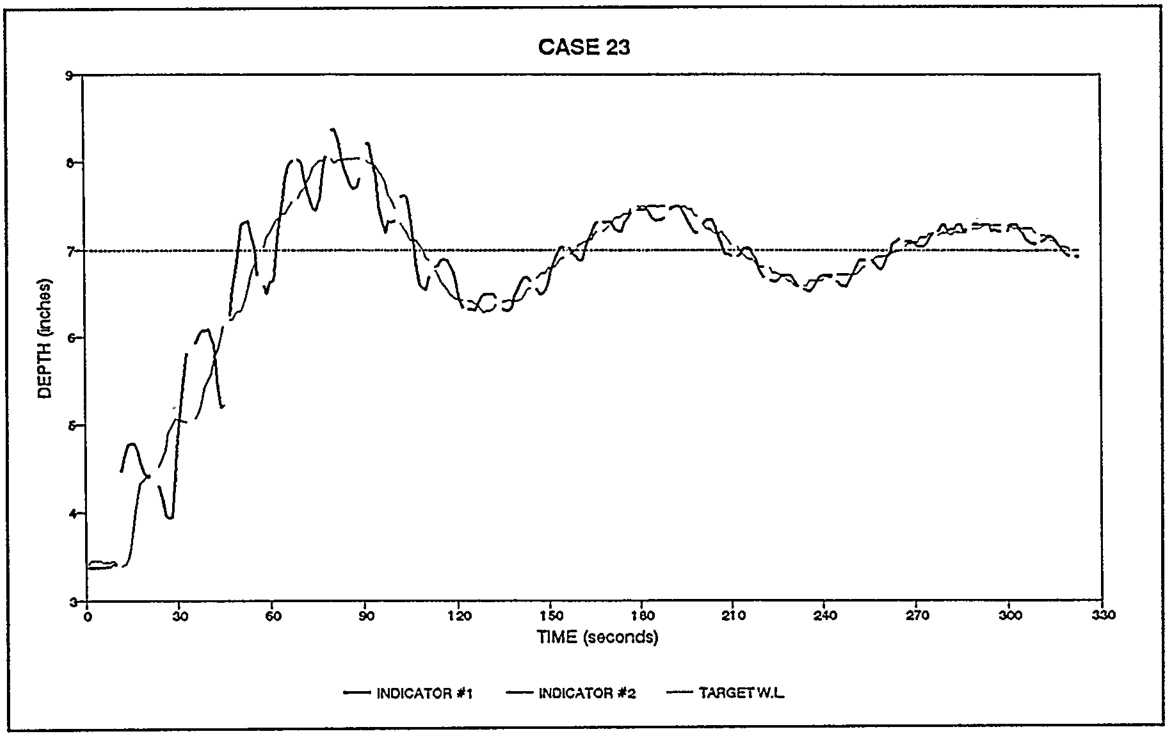


Figure 7.13 - Floating Control, CASE 23
Using Average of Depth Readings at Level Indicator #1
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.

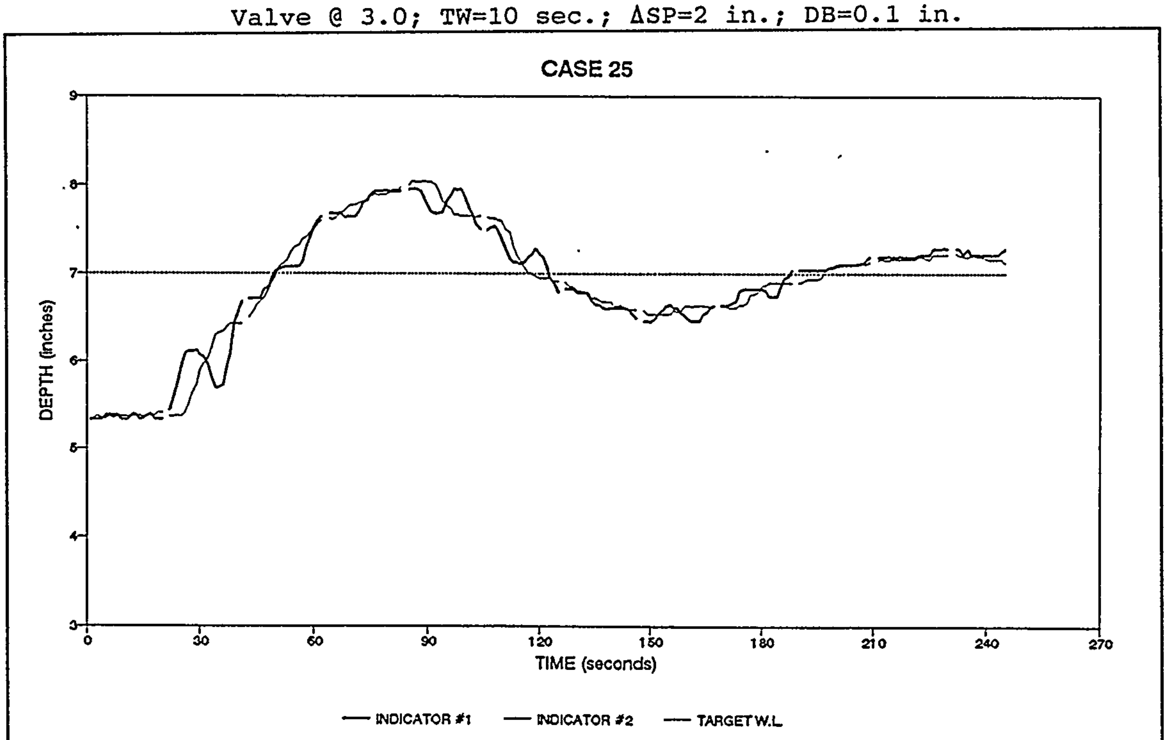


Figure 7.14 - Floating Control, CASE 25
Using Average of Depth Readings at Level Indicator #1
Valve @ 3.0; TW=20 sec.; ΔSP=2 in.; DB=0.1 in.

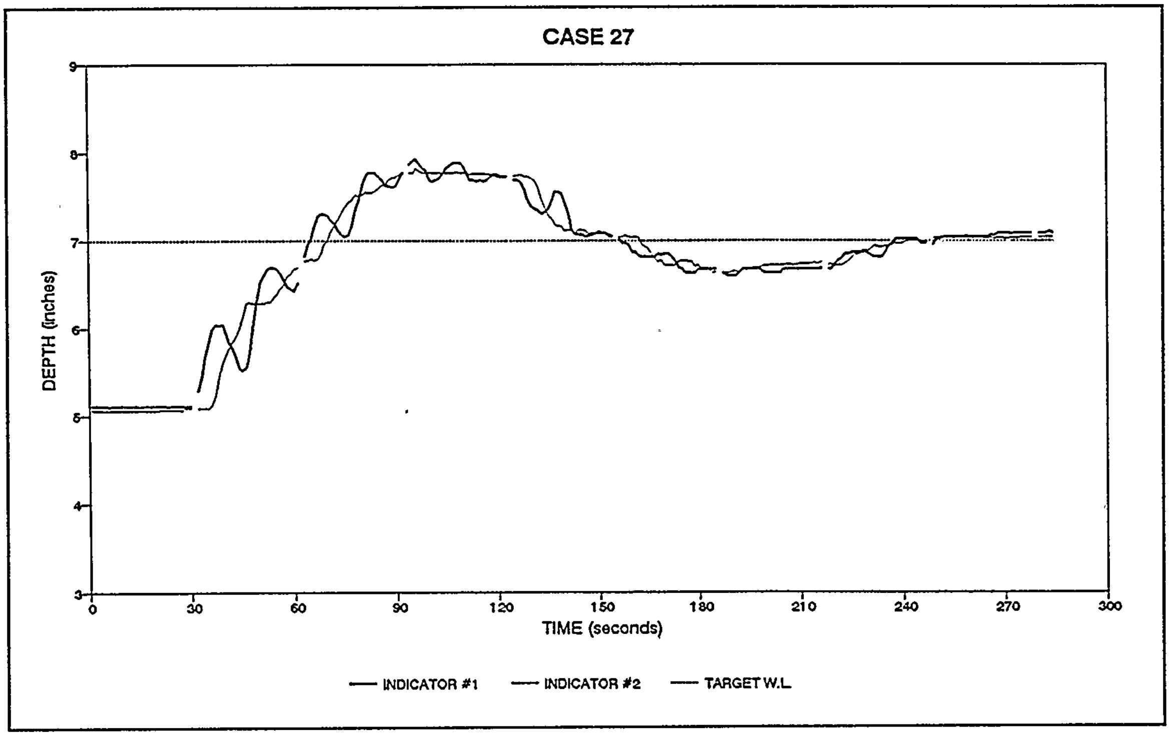


Figure 7.15 - Floating Control, CASE 27
Using Average of Depth Readings at Level Indicator #1
Valve @ 3.0; TW=30 sec.; ΔSP=2 in.; DB=0.1 in.

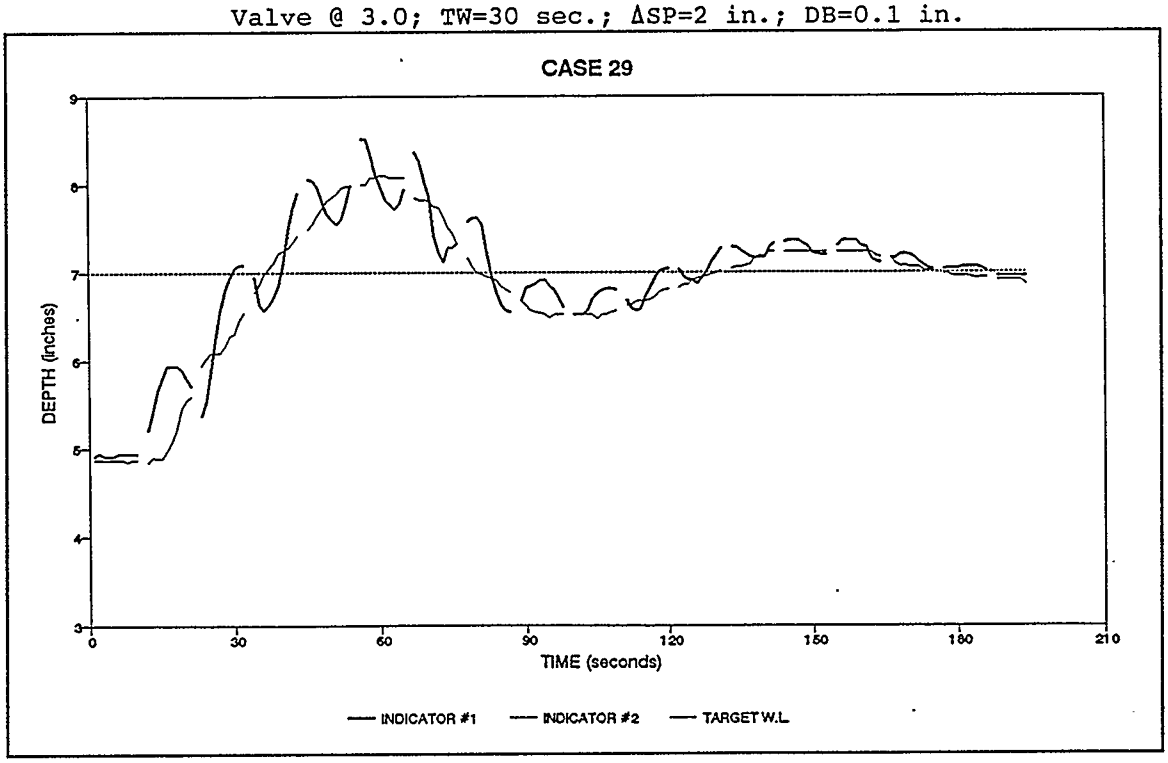


Figure 7.16 - Floating Control, CASE 29
Using Single Depth Readings at Level Indicator #2
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.

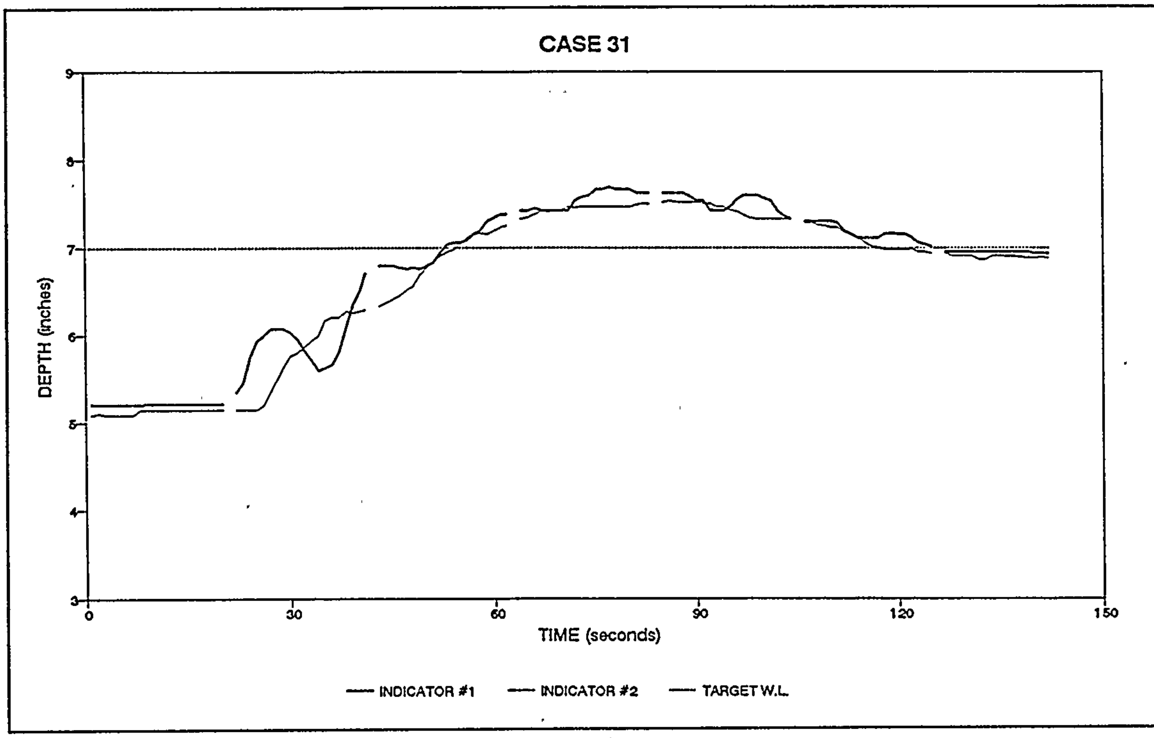


Figure 7.17 - Floating Control, CASE 31
Using Single Depth Readings at Level Indicator #2
Valve @ 3.0; TW=20 sec.; ΔSP=2 in.; DB=0.1 in.

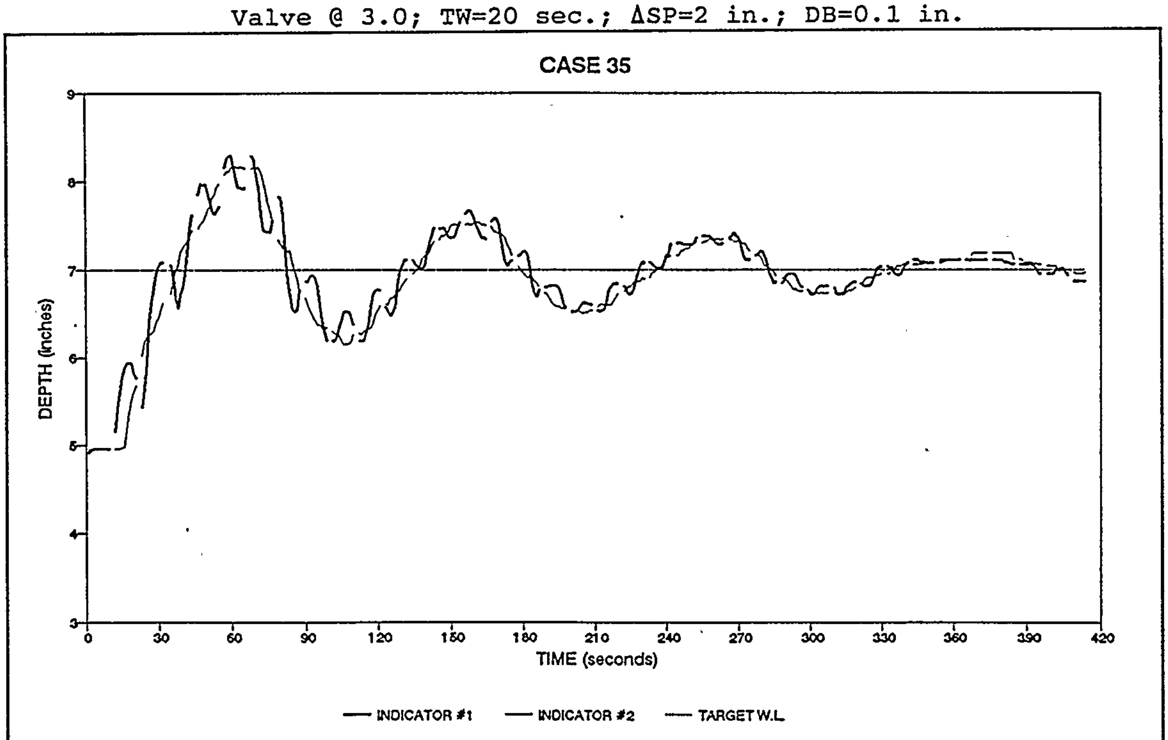


Figure 7.18 - Floating Control, CASE 35
Using Average of Depth Readings Between Level Indicators
#1 and #2 - Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.

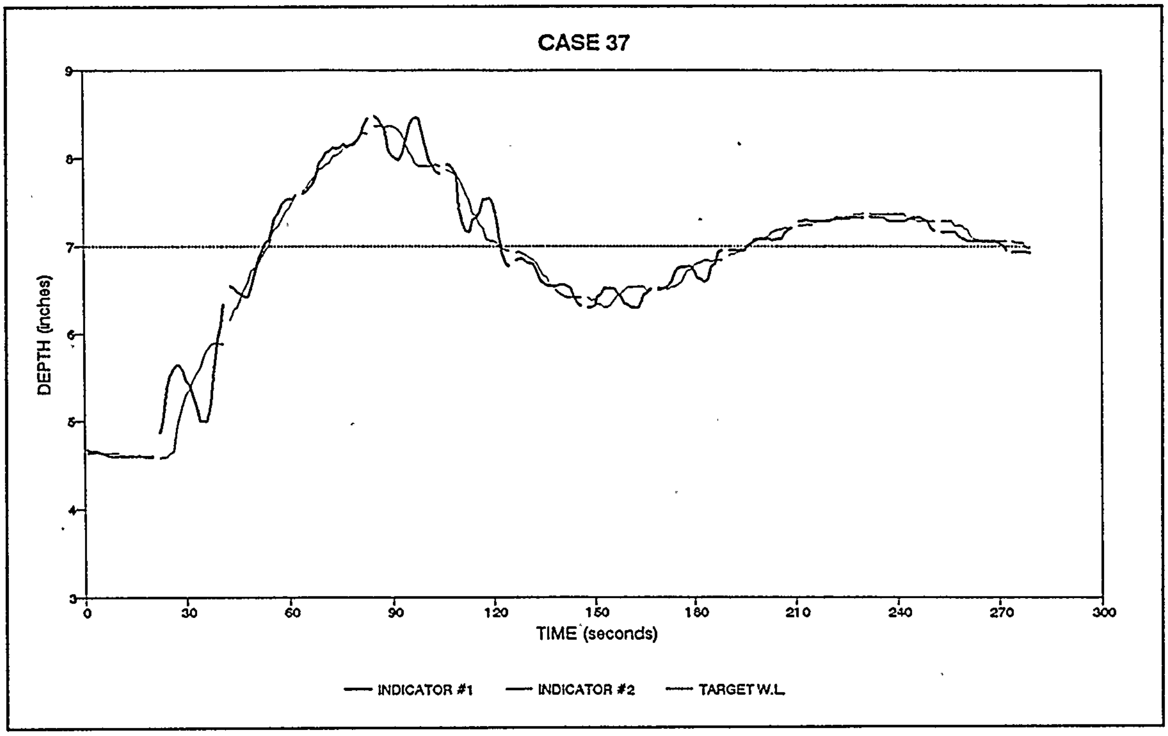


Figure 7.19 - Floating Control, CASE 37
Using Average of Depth Readings Between Level Indicators #1 and #2 - Valve @ 3.0; TW=20 sec.; ΔSP=2 in.; DB=0.1 in.

to a set point increase, the latter caused slightly worst conditions of water level disturbances. To illustrate this point compare Figure 7.4, which shows set point decrease, to its preceding Figure 7.3, which shows set point increase. The water level response was about the same, except that in the set point decrease situation, the target was undershot less than it was overshot with a set point increase. Also, cycling about the set point was less pronounced with a set point decrease. Now compare Figure 7.8 (set point decrease) to its previous Figure 7.7 (set point increase). Like all runs following Case 11, the water levels (depth) for these cases are plotted at 1 second intervals. Previously, Cases 1 to 11 had their water levels plotted at intervals equal to the waiting time. Figure 7.7 clearly shows disturbances in the water level in the form of small waves. These disturbances are not as pronounced in the set point decrease situation of Figures 7.8.

In light of the foregoing, only set point increase situations will be presented for discussion. In fact, no further studies were done of set point decrease following Case 58.

The most single noticeable difference in the results is that as TW increased, cycling about the target decreased. For example, during set point change tests, a value of TW=5 sec. caused about 4 cycles (Figures 7.3 and 7.4), whereas values of TW=20 and 60 sec. caused 1 cycle (Figures 7.5, 7.6 and 7.10). This was consistent when the valve setting was 5.0 (about 82% capacity) or 3.0 (about 38% capacity). Similarly, during flow rate change tests, TW=5 sec. would cause 2 cycles for small ΔQ and 4 cycles for large ΔQ Figure 7.11). By comparison, TW=20 sec. would cause ½ a cycle and 1 cycle respectively (Figure 7.12).

This cycling is caused by the gate movement, but not in the same way as the wave disturbances discussed previously. The waves are localized hydraulic transients caused by actual motion of the gate, whereas the cycling is caused by a "back-and-forth" motion in gate adjustments. This cycling is a higher order level of hydraulic transient normally associated with gate operation, that travels between structures in a reach of canal. Consider, first of all, the runs using TW=5 sec.. Equilibrium about the new target was not achieved until well after 2 min., which means that gate adjustments could potentially have been executed in the order of 24 times. The response in water level to a new gate setting (rise or drop) was much slower, so gate adjustment was being made faster than the water level was responding.

During low values of Q and when ΔSP=5 in., upward gate adjustments continued even when the crest rose above the water level. To prevent this, an override was added in the program to avoid a gate adjustment in these situations.

Higher values of TW meant that the gate adjustments were being made slow enough for the water level to catch up. At TW=20 or 60 sec., the time to equilibrium was less than 1½ min. at the higher Q, which meant that no more than 4 gate adjustments were required. This was only slightly increased at the lower Q (equilibrium by 2 min.).

Because of the frequent cycling the minimum TW used in future cases was limited to 10 sec., except for a few cases under P Control. Up to 4 cycles were still occurring with TW=10 sec. during high values of ΔSP (Figure 7.9), but it was considered desirable to use this time as a benchmark for analysing other control algorithms; one in which instability is known to occur. Also, future runs did not use values of TW as high as 60 sec..

In Chapter 6.0 it was mentioned that some of the early control programs resulted in data gaps caused by gate adjustment timer sequences. Figures 7.13 to 7.19 illustrate this point, which is evident by the broken lines. Later control programs corrected this problem during PI, PD and PID Control case studies.

Cases 23 to 40 are repetitious to some of their previous cases, but their control algorithms were altered to analyze the gate and response characteristics when based on other than single depth readings at Level Indicator #1. Figures 7.13 and 7.14 show the results of case studies in which the control algorithm was based on an average of depth readings at Level Indicator #1 during the waiting period, taken at intervals of 1 sec.. These compare closest in operating parameters to Figures 7.9 and 7.10. Interestingly, these new cases exhibited very definite and prolonged cycling about the target, much more so than the previous cases in which the algorithm was based on single depth readings. The amplitude of the first cycle, which is the worst overshoot, is about the same, but the length of each cycle is longer in the latest cases.

With Cases 29 to 34, the control algorithm was based on single depth readings at Level Indicator #2. Comparing Figures 7.16 and 7.17 to Figures 7.9 and 7.10, the response in upstream level is almost identical. The only noticeable difference is that the amplitude of the first cycle in the earlier cases was higher, but this is probably due to the fact that ΔSP was over twice that of Cases 29 to 34.

Finally, Cases 35 to 40 have their control algorithm based on an average of depth readings at both Level Indicators #1 and #2. Those cases exhibited worse cycling (more gate movement) than even the cases when the control algorithm was based on an average of depths at Level Indicator #1, and the amplitude of the first cycles were higher (see Figures 7.18 and 7.19).

Considering the poorer showing of these latest case studies (Figures 7.20 to 7.28), all future runs were carried out with the control algorithm based on single depth readings at Level Indicator #1.

Level Indicator #2 does not serve a necessary purpose for future gate control operations, but it does provide a very useful comparison in the response of the upstream water level. Referring to Figures 7.13 to 7.19, the water level at Level Indicator #2 did not exhibit the small wave disturbances found at Level Indicator #1. This proves that the gate movement itself is triggering this disturbance, and the short distance between the two Level Indicators is sufficient for these localized transients to be dampened out. It is further evident that the water surface response at Level Indicator #2 lagged that at Level Indicator #1 by about 5 seconds. This lag is the wave travel time between these two locations.

The affect of the magnitude in ΔSP is evident by comparing Figures 7.1 and 7.2 to Figures 7.3 and 7.5 respectively. With the larger ΔSP situations, the amplitude of the first cycle was considerably larger than the smaller ΔSP, but the degree of cycling was not appreciably different.

7.2 P Control

Table 7.2 summarizes the parameters and operating conditions tested under proportional control. In addition to the previous notation, the following is added:

K = Proportional gain factor

Figures 7.20 to 7.2843 are the plotted results of some key cases tested (set point decrease not included). All cases exhibited an improved response in terms of reducing or eliminating cycling about the set point. Case studies which used TW=5 and 10 seconds showed the most dramatic improvement, particularly at values of K=0.25 and 0.5. When cycling was eliminated stabilization about the target was achieved sooner than when cycling occurred with Floating Control.

As expected, larger values of K and TW in combination performed equally

Table 7.2 - Summary of Case Studies for P Control

Case No.	Valve	TW (sec.)	ΔSP (in.)	DB (in.)	K
41, 42	3.0	5	2	0.1	0.25
43, 44	3.0	5	2	0.1	0.5
45, 46	3.0	5	2	0.1	0.75
47, 48	3.0	10	2	0.1	0.25
49, 50	3.0	10	2	0.1	0.5
51, 52	3.0	10	2	0.1	0.75
53, 54	3.0	20	2	0.1	0.5
55, 56	3.0	20	2	0.1	0.75
57, 58	3.0	10	2	0.1	1.0
59	varies	10	0	0.1	0.5
60	varies	5	0	0.1	0.5
129	3.0	20	2	0.1	0.5
137	3.0	10	2	0.1	0.5
207 (1)	varies	10	0	0.1	0.25
208 (1)	varies	20	0	0.1	0.25
209 (1)	varies	10	0	0.1	0.5
210 (1)	varies	20	0	0.1	0.5
211	varies	10	0	0.1	0.25

(1) Total Correction is compared to Deadband to determine if adjustment is required.

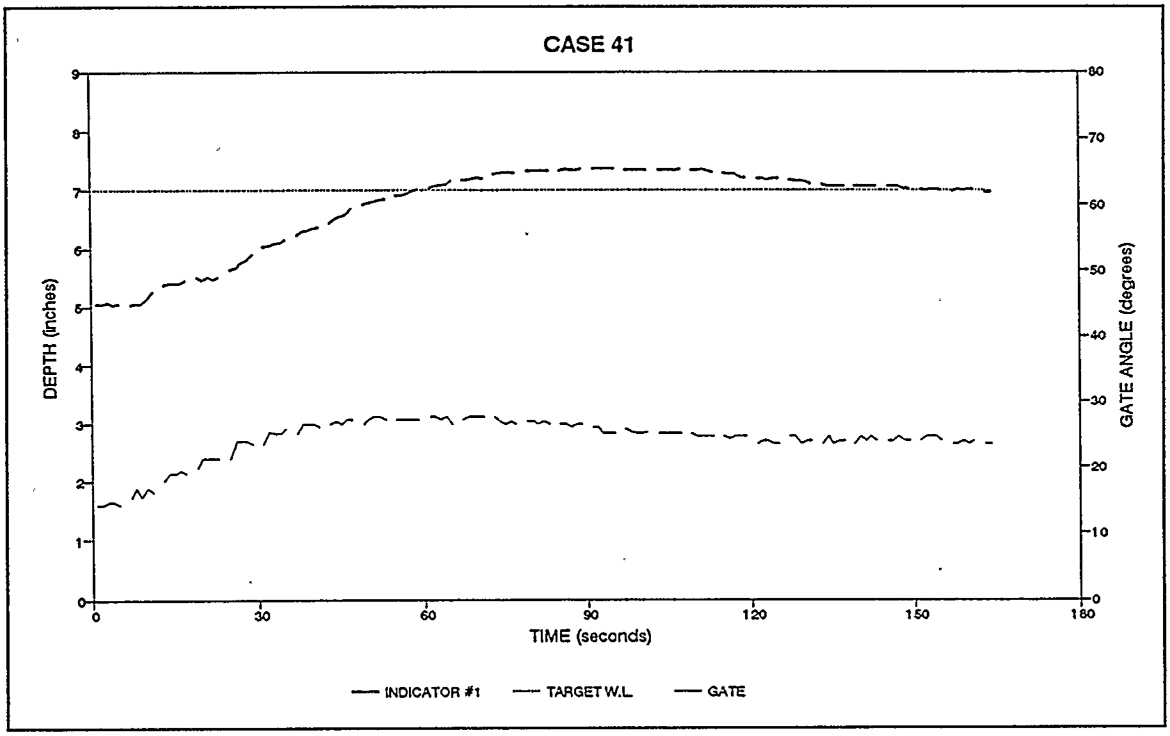


Figure 7.20 - P Control,CASE 41
Valve @ 3.0; TW=5 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.25

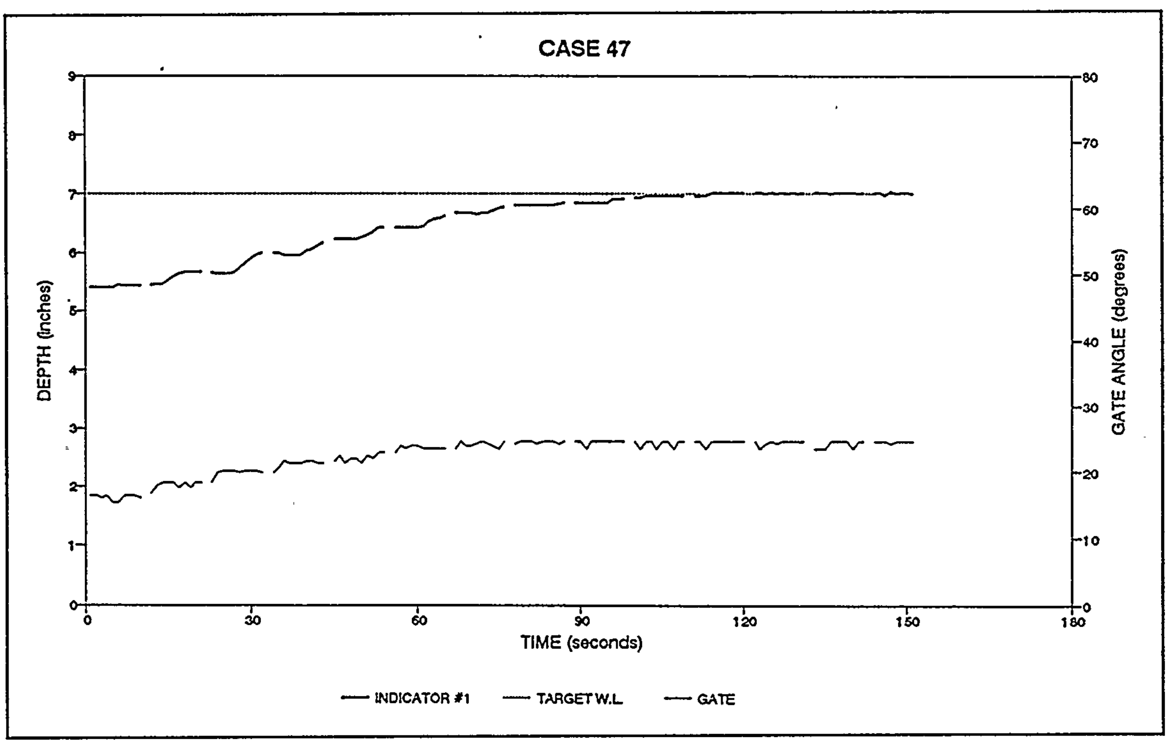


Figure 7.21 - P Control, CASE 47
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.25

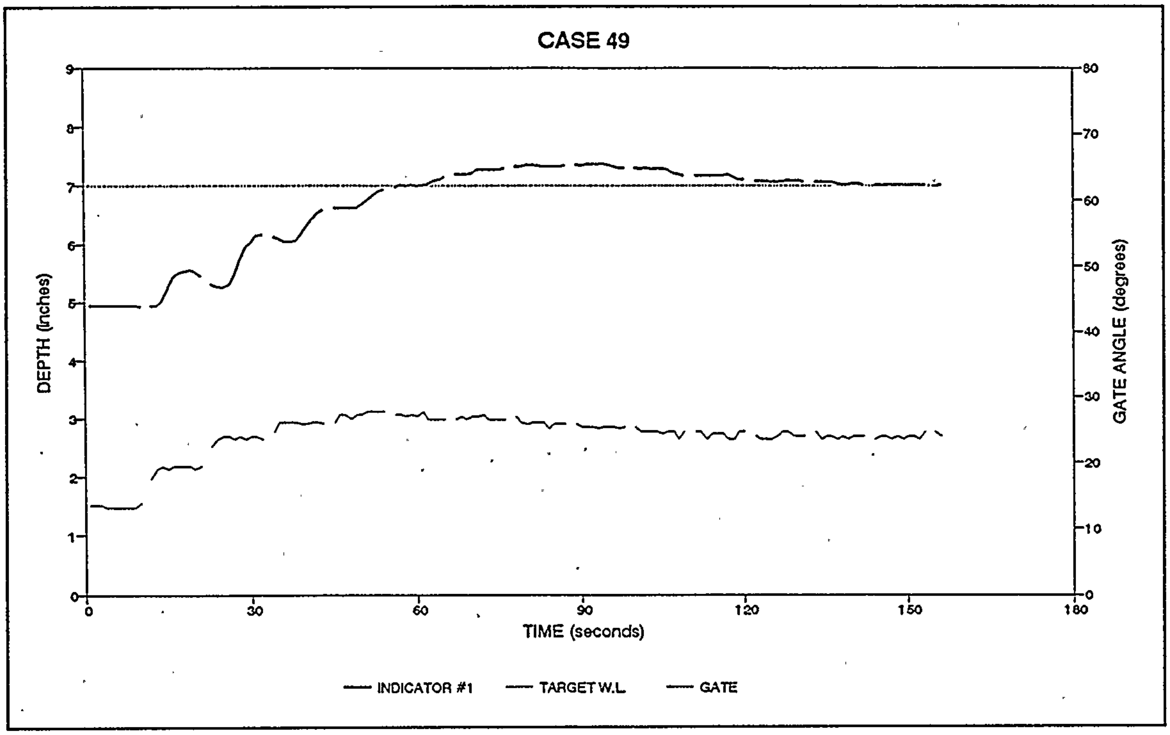


Figure 7.22 - P Control, CASE 49
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.5

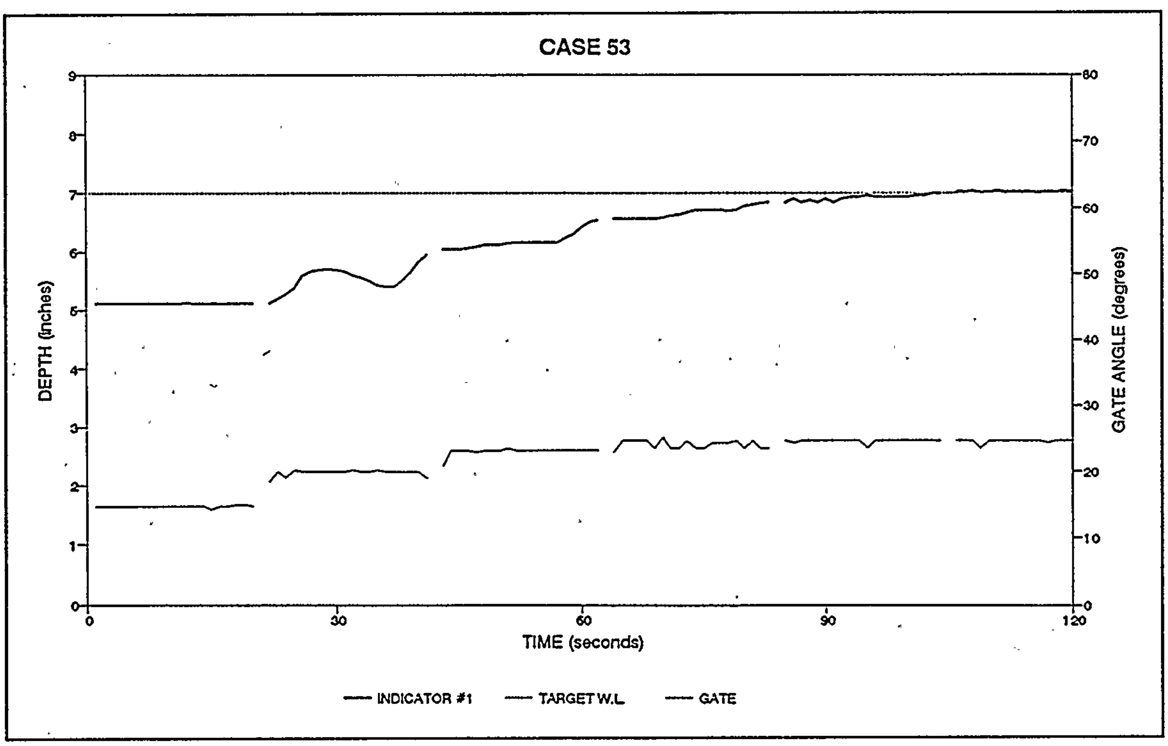


Figure 7.23 - P Control, CASE 53
Valve @ 3.0; TW=20 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.5

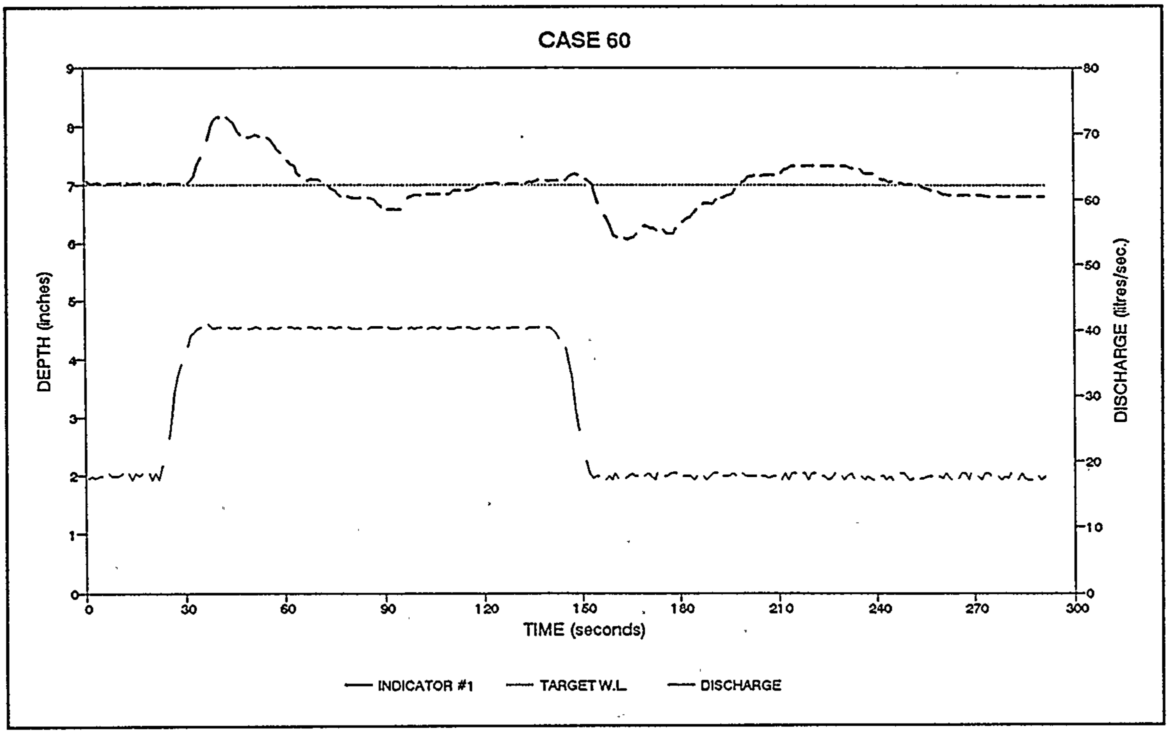


Figure 7.24 - P Control, CASE 60
Q varies; TW=5 sec.; DB=0.1 in.; K=0.5

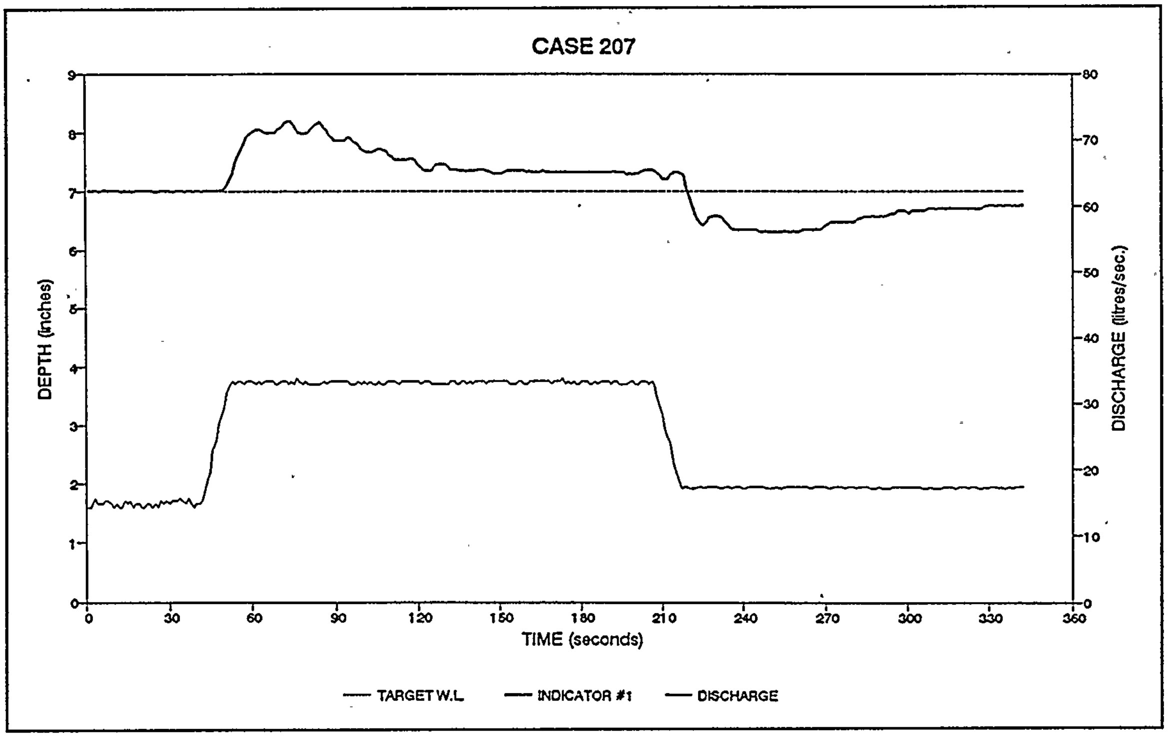


Figure 7.25 - P Control, CASE 207
Total Correction Compared to Deadband
Q varies; TW=10 sec.; DB=0.1 in.; K=0.25

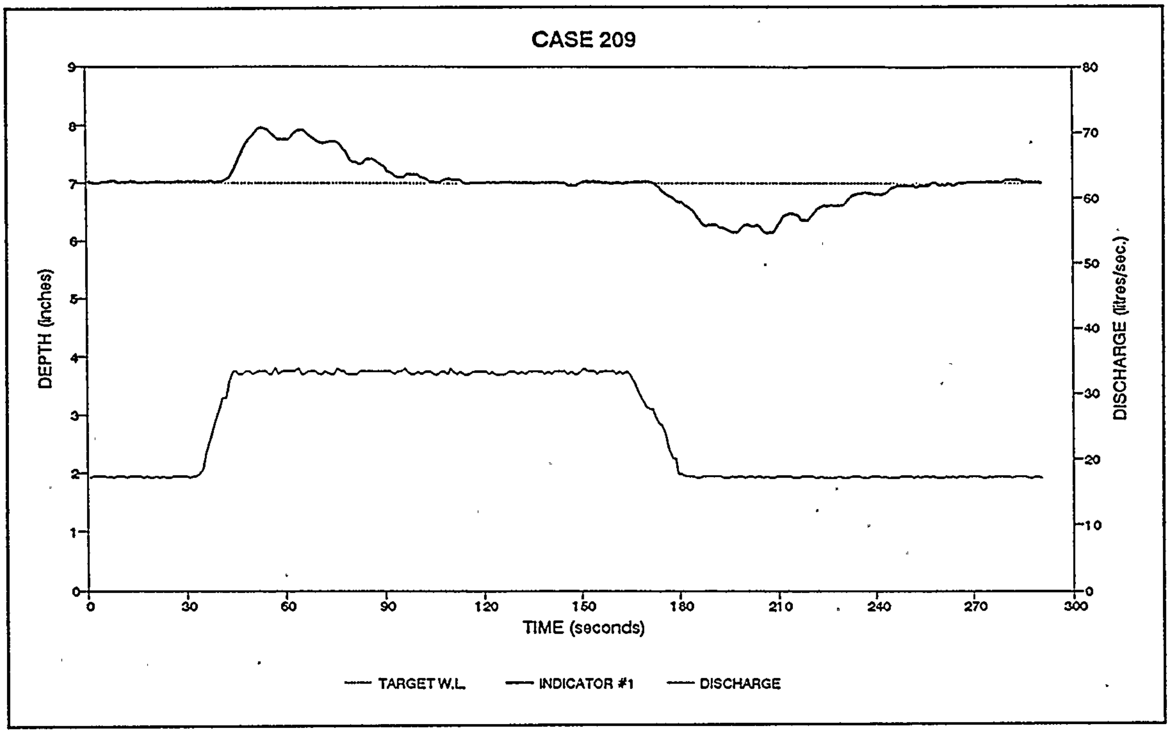


Figure 7.26 - P Control, CASE 209
Total Correction Compared to Deadband
Q varies; TW=10 sec.; DB=0.1 in.; K=0.5

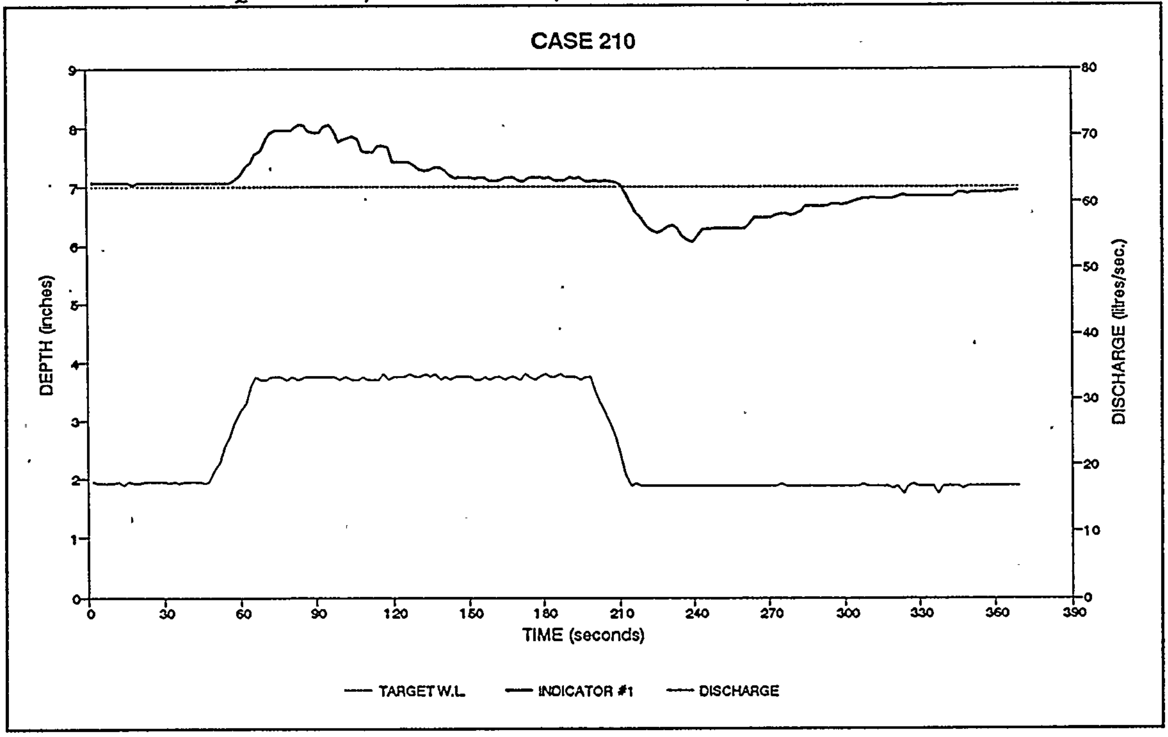


Figure 7.27 - P Control, CASE 210
Total Correction Compared to Deadband
Q varies; TW=20 sec.; DB=0.1 in.; K=0.5

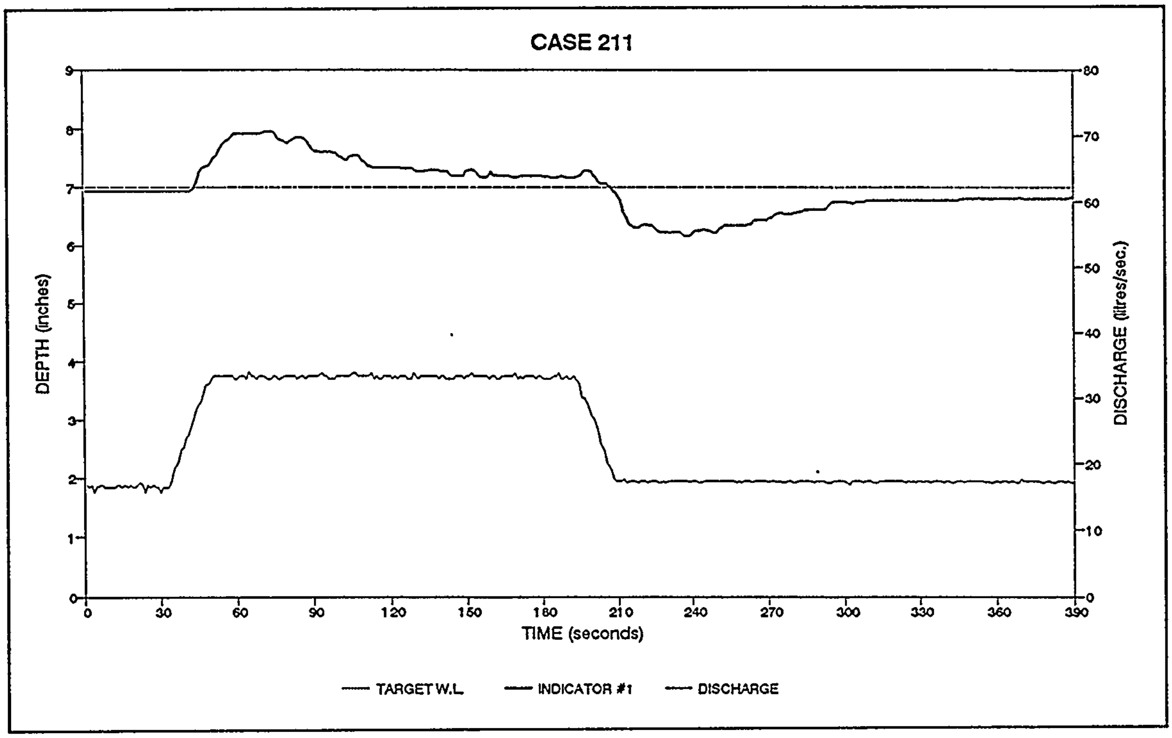


Figure 7.28 - P Control, CASE 211
Total Correction Compared to Error
Q varies; TW=10 sec.; DB=0.1 in.; K=0.25

well as smaller values of K and TW in combination. If K/TW was constant, the characteristics were similar. For example, consider the following for the set point increase situations:

$\frac{K}{TW}=0.025$	No cycling; target stabilized by 100 sec,; see Figures 7.21 and 7.23.
$\frac{K}{TW}=0.05$	One-half cycle; target stabilized by 140 sec.; see Figures 7.20 and 7.22.

When K=1.0 the algorithm becomes transformed to Floating Control.

In situations when the set point was constant and the flow rate varied, a wider range of K/TW (up to 0.05) resulted in stabilization about the target without cycling. However, in those situations it took almost twice as long for the water level to return to the set point compared to cases when some cycling occurs (Figure 7.24 - K/TW=0.1). If it is more important that deviation about the set point be minimized, and some cycling is acceptable, then situations with higher ratios of K/TW will be preferred.

When the flow rate was constant (set point change situations), a value of K=0.25 eliminates the wave disturbances observed during floating control cases (Figures 7.20 and 7.22). Even K=0.5 eliminated these disturbances as the water level approached the target, which essentially means as error diminished (Figure 7.33). These values of proportional gain sufficiently reduced gate movements to avoid localized transients. However, with flow rate change situations, these observations were only made (to a lesser extent) when the gate responded to a decrease in flow (Figure 7.25). This illustrates that these transients were caused by changes in flow rate as well as gate movements.

With flow rate change situations such as Case 207 (Figure 7.25), the equilibrium water level was outside the deadband range of WL ± 0.1 in.. This illustrates a fundamental difference in the control program structure used with these later case studies. Previously, gate adjustments were not initiated unless the water level was outside this range. In those situations following Case 60, gate adjustments were made only if the total correction was larger than the deadband, which in this case was ± 0.1 in.. For situations such as Case 207 the proportional gain reduced the correction to values within this tolerance so that adjustments were not made, thus resulting in the large steady state error remaining. When K=0.5 (Figure 7.26) the correction was still large enough to initiate gate adjustment, and the accuracy in water level was achieved as expected.

In an attempt to improve the above situation, the control program was modified so that gate adjustment would continue if the error was larger than the deadband. Case 211 (Figure 7.28) shows that improvements were made, but a large steady state error still existed. This was caused by the low value of K, which caused such small adjustments in gate setting that water level response approached the outside limits of the deadband.

7.3 PI Control

Table 7.3 summarizes the parameters and operating conditions tested using proportional plus integral control. In addition to the previous notation, the following is added:

RE = Integral reset time

Figures 7.29 to 7.36 are the plotted results of some key PI control cases tested.

Integral action is intended to provide the dominating correction when the error is large. When the error is small, such as when the water level approaches the target, this action becomes small and proportional correction will dominate. However, as shown by Figures 7.29 and 7.30, when RE became too small integral action dominated most of the time, thus causing instability. During the testing even lower values of RE were used than reported herein, which caused such high values of erroneous corrections that illegal quantity errors occurred in the program.

As RE increased, the water level response improved in terms of cycling about the target (Figure 7.31). However, if it became large then the gate responded more as proportional control. This can be illustrated by comparing PI control Cases 149 and 133 (Figures 7.32 and 7.34) to P control Cases 47 and 49 (Figures 7.21 and 7.22).

Table 7.3 - Summary of Case Studies for PI Control

Case No.	Valve	TW (sec.)	ΔSP (in.)	DB (in.)	K	RE
61	3.0	10	2	0.1	0.25	10
62	3.0	10	2	0.1	0.25	20
63	3.0	10	2	0.1	0.25	50
64	3.0	10	2	0.1	0.25	100
65	3.0	20	2	0.1	0.25	50
66	3.0	20	2	0.1	0.25	100
67	3.0	20	2	0.1	0.25	200
127	3.0	20	2	0.1	0.5	1000
133	3.0	10	2	0.1	0.5	500
148B	3.0	10	2	0.1	0.5	200
149	3.0	10	2	0.1	0.25	250
212	varies	10	0	0.1	0.25	100
213	varies	20	0	0.1	0.25	100
214	varies	20	0	0.1	0.25	200
215	varies	10	0	0.1	0.5	200
216	varies	20	0	0.1	0.5	400

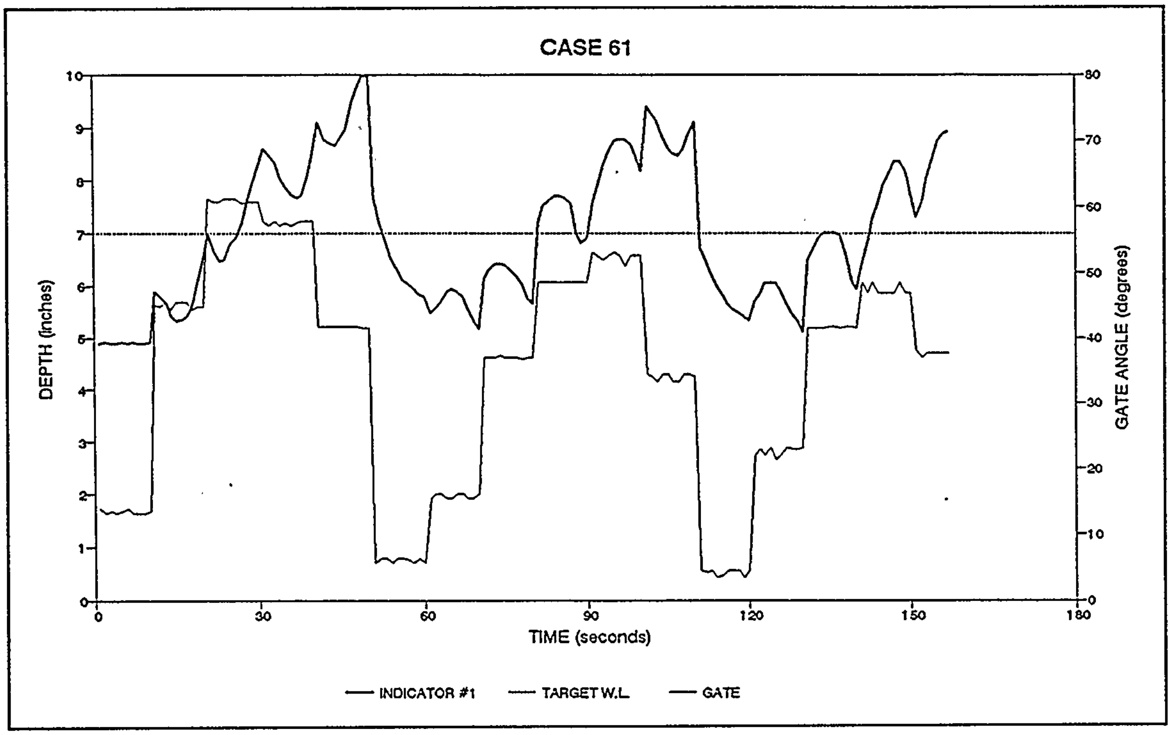


Figure 7.29 - PI Control, CASE 61
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.25; RE=10

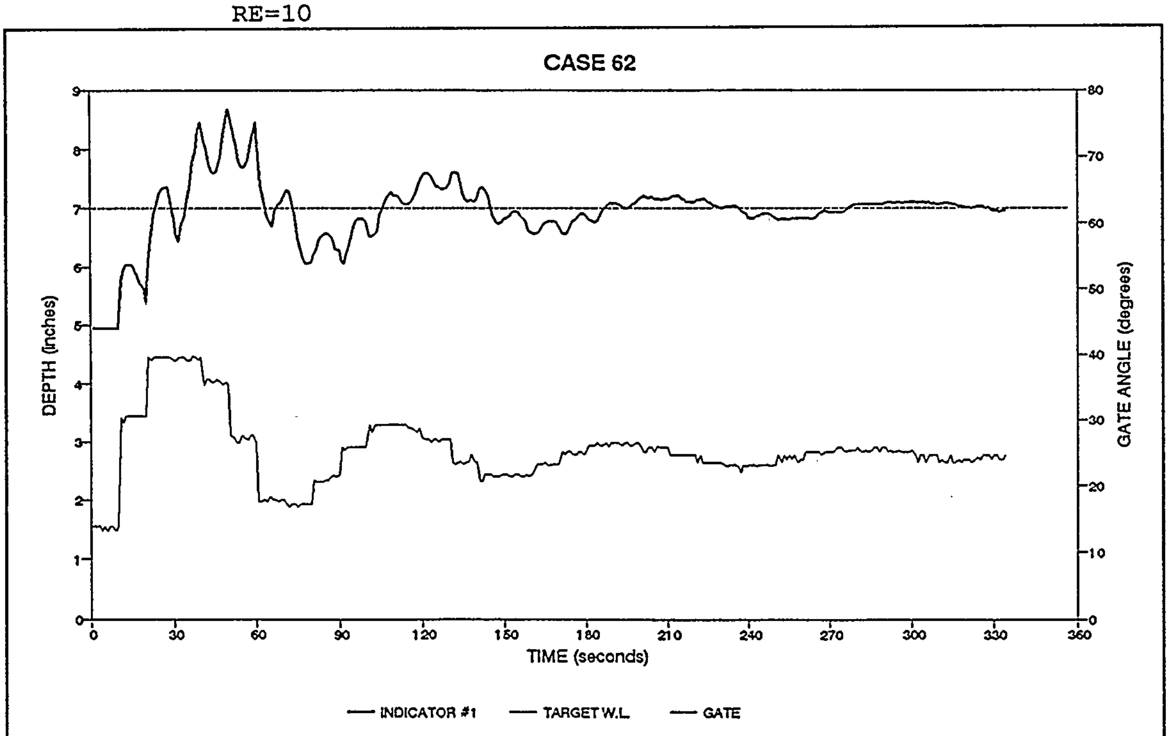


Figure 7.30 - PI Control, CASE 62
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.25; RE=20

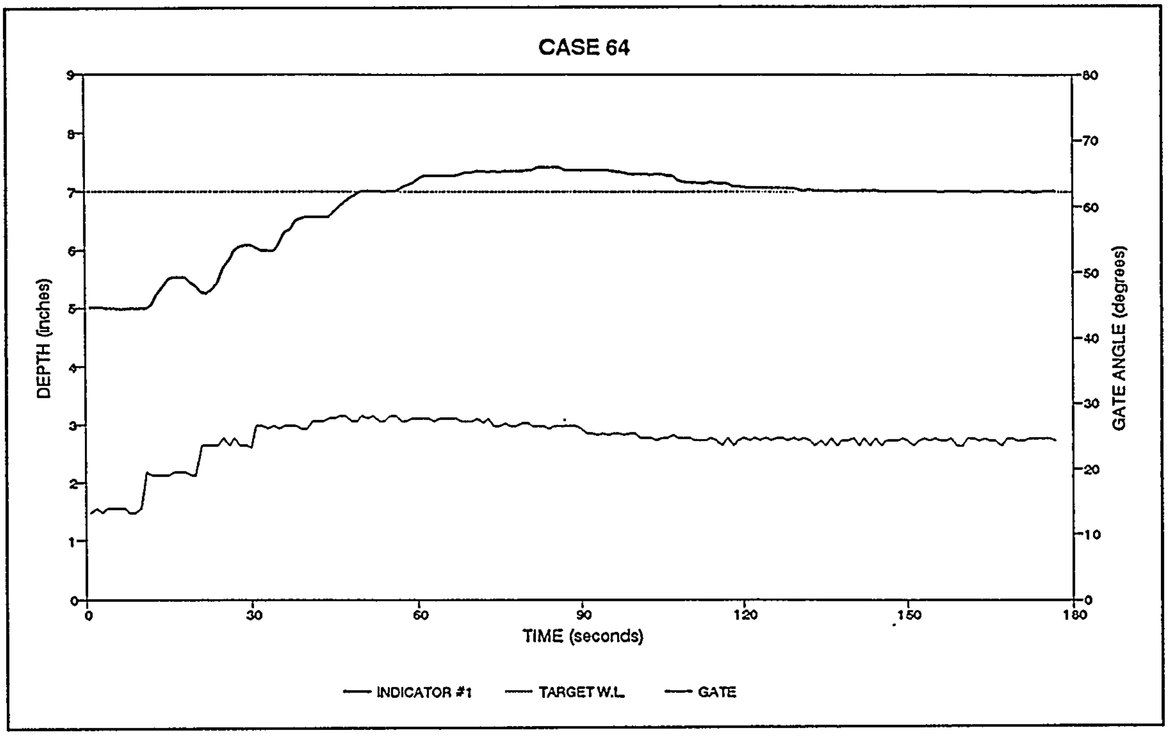


Figure 7.31 - PI Control, CASE 64
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.25; RE=100

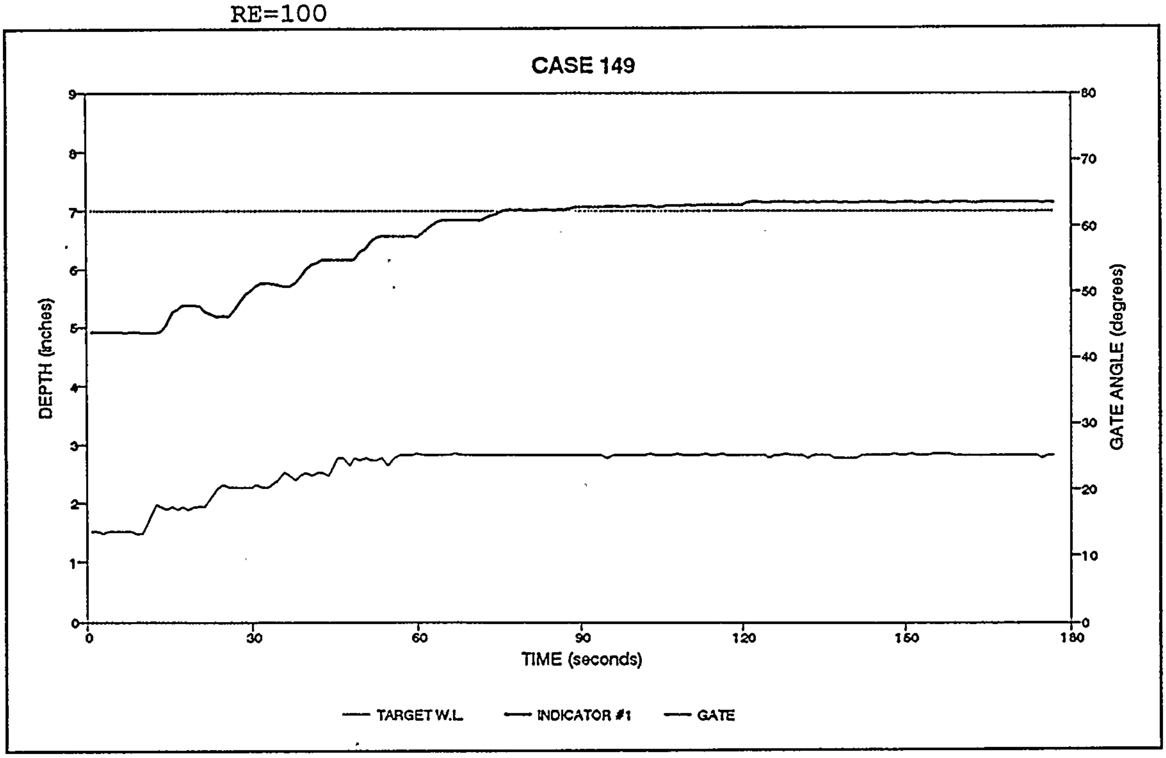


Figure 7.32 - PI Control, CASE 149
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.25; RE=250

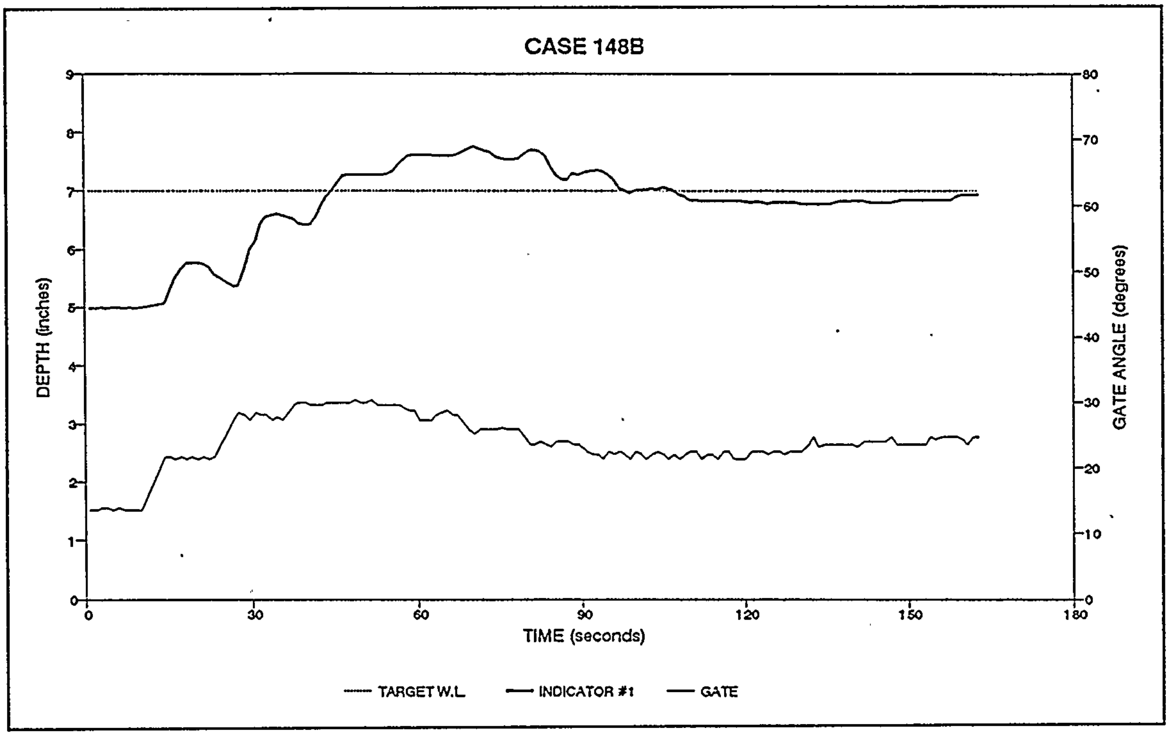


Figure 7.33 - PI Control, CASE 148B
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.5; RE=200

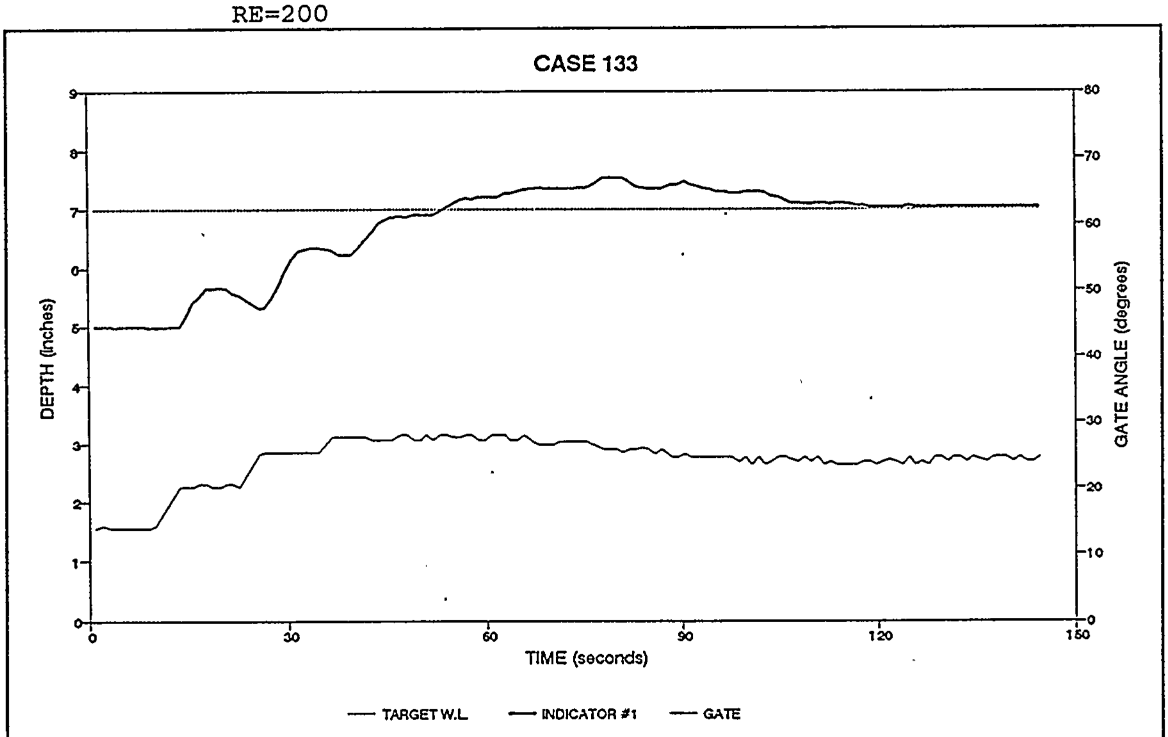


Figure 7.34 - PI Control, CASE 133
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.5; RE=500

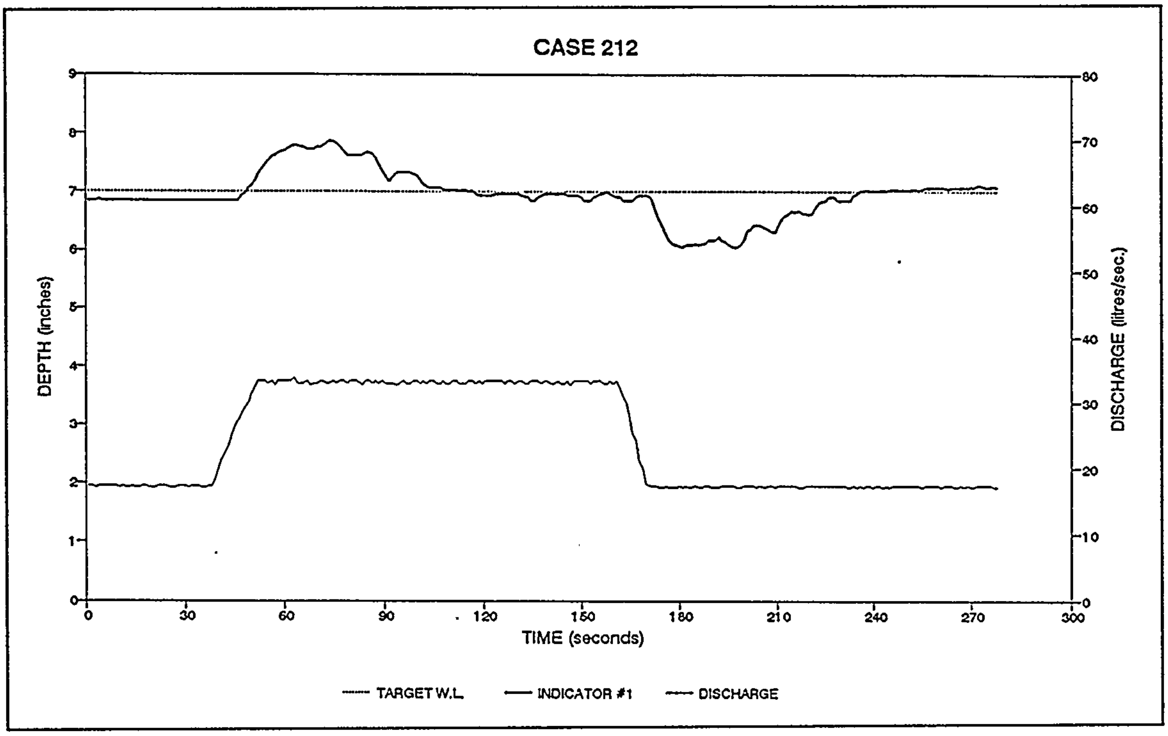


Figure 7.35 - PI Control, CASE 212
Q Varies; TW=10 sec.; DB=0.1 in.; K=0.25; RE=100

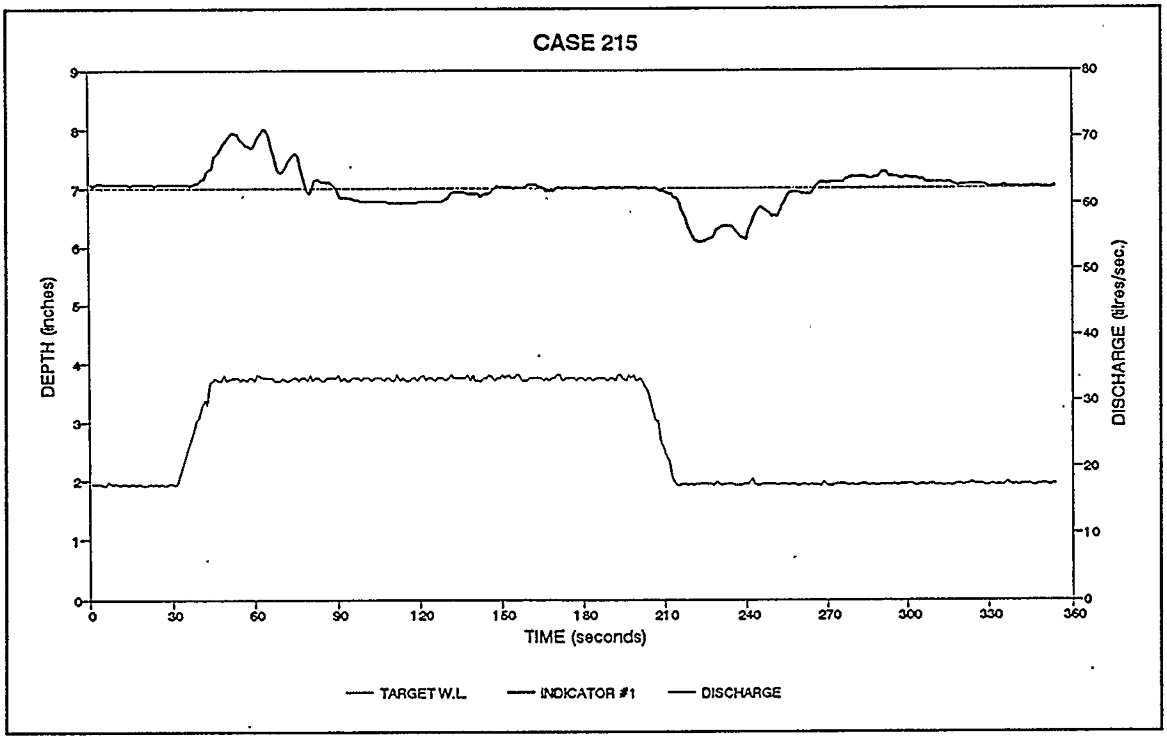


Figure 7.36 - PI Control, CASE 215
Q Varies; TW=10 sec.; DB=0.1 in.; K=0.5; RE=200

It was found that acceptable results could be attained if the following relationship was adhered to:

$$\frac{K(TW)}{RE} \approx 0.025$$

This provides a reasonably quick response time with minimal cycling. Figures 7.31 and 7.33 illustrate a typical response characteristic for this relationship. As K(TW)/RE increased greater than 0.025, cycling would occur or instability would result (if high enough).

Integral control eliminated the steady state error inherent with P control. Recall that with the latter using K=0.25, the water level stabilized at the outer limit of the deadband range. With integral action added, the water level stabilized almost precisely at the set point, and in a shorter period of time (Figures 7.25 and 7.28 to 7.35). This was consistent throughout most of the test cases. All of the case studies for PI control used algorithms that compared total correction to the deadband to determine if gate adjustments were necessary.

Values of K larger than 0.5 were not tested. It was evident from the P control studies that overshooting of the target, and consequently cycling, would become more prevalent.

7.4 PD Control

Table 7.4 summarizes the parameters and operating conditions tested using proportional plus derivative control. In addition to the previous notation, the following is added:

RA = Derivative rate gain

Figures 7.37 to 7.41 are the plotted results of some key PD Control cases tested.

The principle of derivative action is that it acts opposite to proportional and/or integral action to prevent large corrections from causing the target to be excessively overshot or undershot, thus causing cycling or instability. Several cases were studied using positive values of RA. Figure 7.37 illustrates that the gate response is opposite to what is expected, causing worse conditions than P control alone. However, negative values of RA provide the results expected. It was found that a wide range of values for RA (less than zero) provided acceptable results, but the following relationship was established as a guide:

$$\frac{K(RA)}{TW} \approx -0.25$$

Figures 7.38 and 7.41 illustrate typical response characteristics for this relationship. When K(RA)/TW approached -2, instability would start (Figure 7.39). Figure 7.40 shows extreme instability at K(RA)/TW=-4.

When K=0.25, derivative action resulted in a longer time until the target was reached. In fact, the response in water level was excessively flat with a resulting large steady state error (Figure 7.41). Because the

Table 7.4 - Summary of Case Studies for PD Control

Case No.	Valve	TW (sec.)	ΔSP (in.)	DB (in.)	K	RA
68	3.0	10	2	0.1	0.75	0.1
69	3.0	10	2	0.1	1.0	0.1
70	3.0	10	2	0.1	1.0	0.25
71	3.0	10	2	0.1	1.0	0.5
72	3.0	10	2	0.1	1.0	1
73	3.0	10	2	0.1	1.0	2
74	3.0	10	2	0.1	1.0	5
75	3.0	10	2	0.1	1.0	10
76	3.0	10	2	0.1	1.0	20
77	3.0	20	2	0.1	1.0	0.1
78	3.0	20	2	0.1	1.0	0.25
79	3.0	20	2	0.1	1.0	0.5
80	3.0	20	2	0.1	1.0	1
81	3.0	20	2	0.1	1.0	5
82	3.0	20	2	0.1	1.0	10
83	3.0	20	2	0.1	1.0	20
128	3.0	20	2	0.1	0.5	20
134	3.0	10	2	0.1	0.5	10
135	3.0	10	2	0.1	0.5	-10
136	3.0	10	2	0.1	0.5	-5
138	3.0	10	2	0.1	0.5	-20
139	3.0	10	2	0.1	0.5	-40
140	3.0	10	2	0.1	0.5	-80
164	3.0	10	2	0.1	0.25	-2.5
165	3.0	10	2	0.1	0.25	-5
166	3.0	10	2	0.1	0.25	-10
167	3.0	10	2	0.1	0.25	-20
221	varies	10	0	0.1	0.25	-20

Table 7.4 (con't.)

Case No.	Valve	TW (sec.)	ΔSP (in.)	DB (in.)	K	RA
222	varies	10	0	0.1	0.5	-10

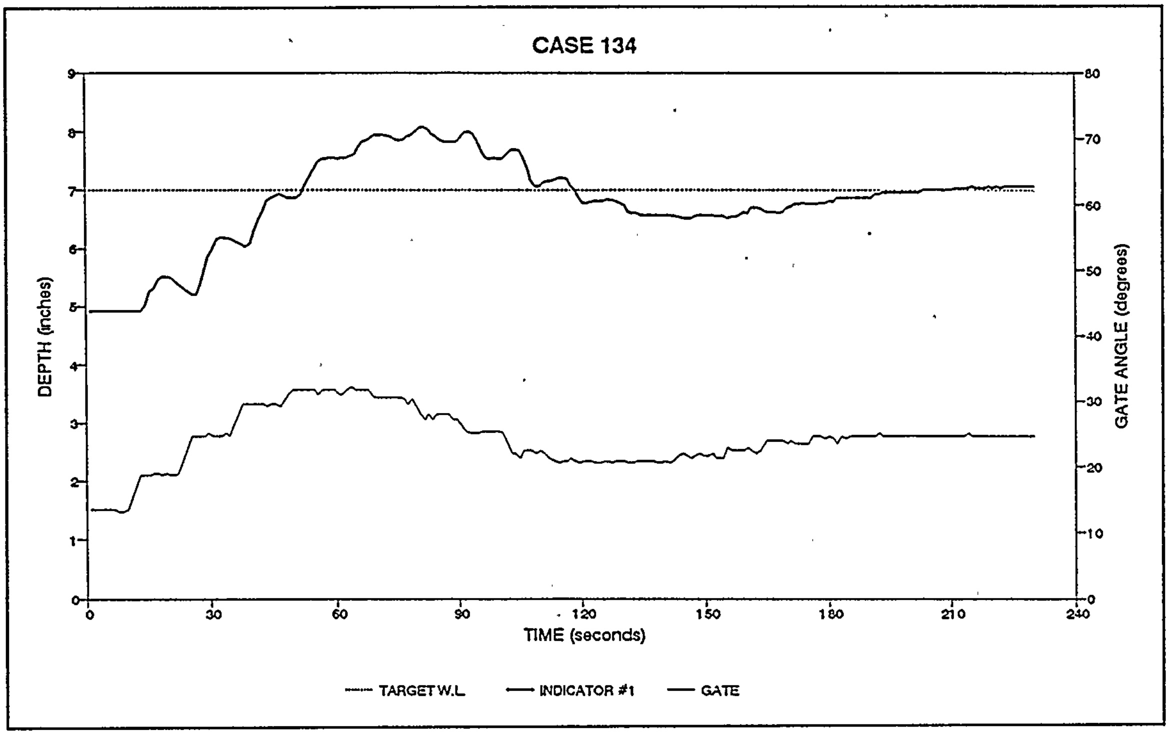


Figure 7.37 - PD Control, CASE 134
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.5; RA=10

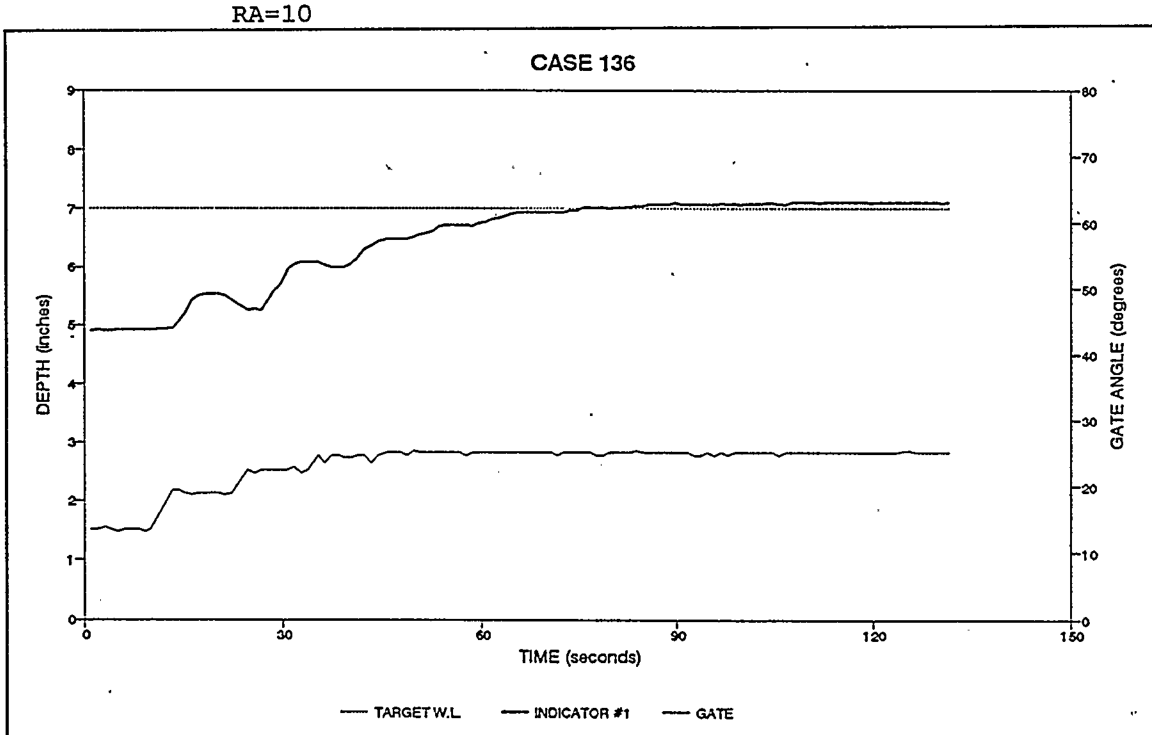


Figure 7.38 - PD Control, CASE 136
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.5; RA=-5

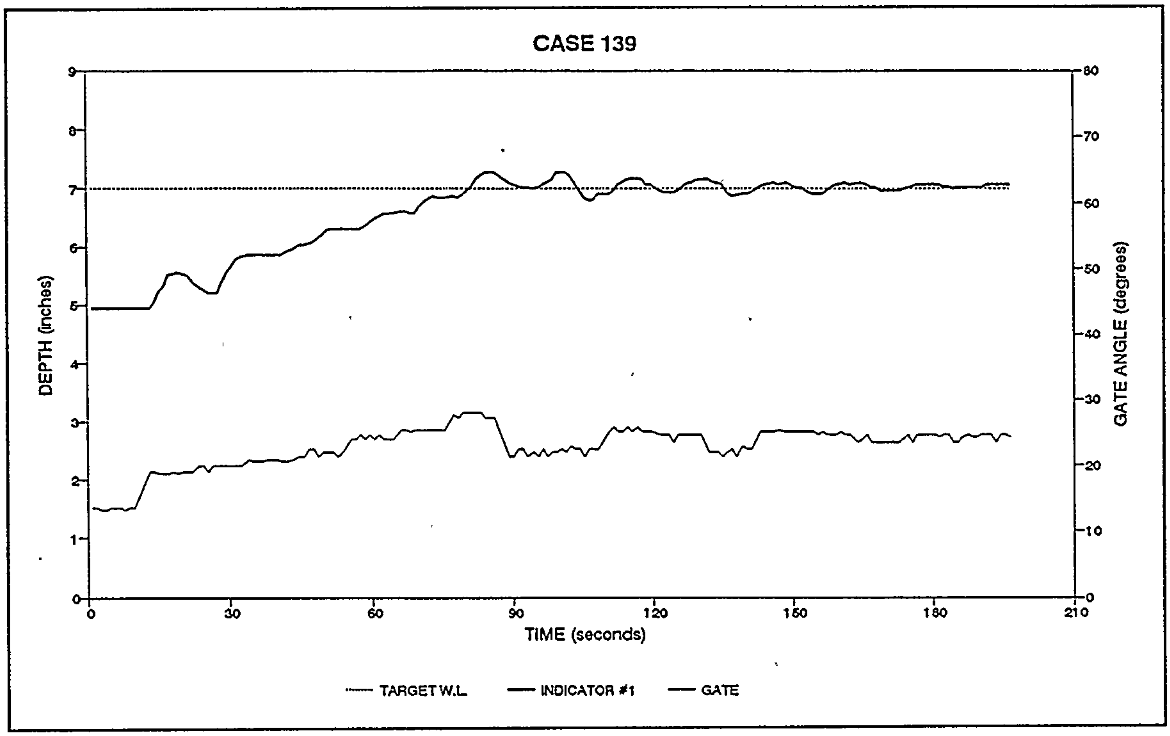


Figure 7.39 - PD Control, CASE 139
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.5; RA=-40

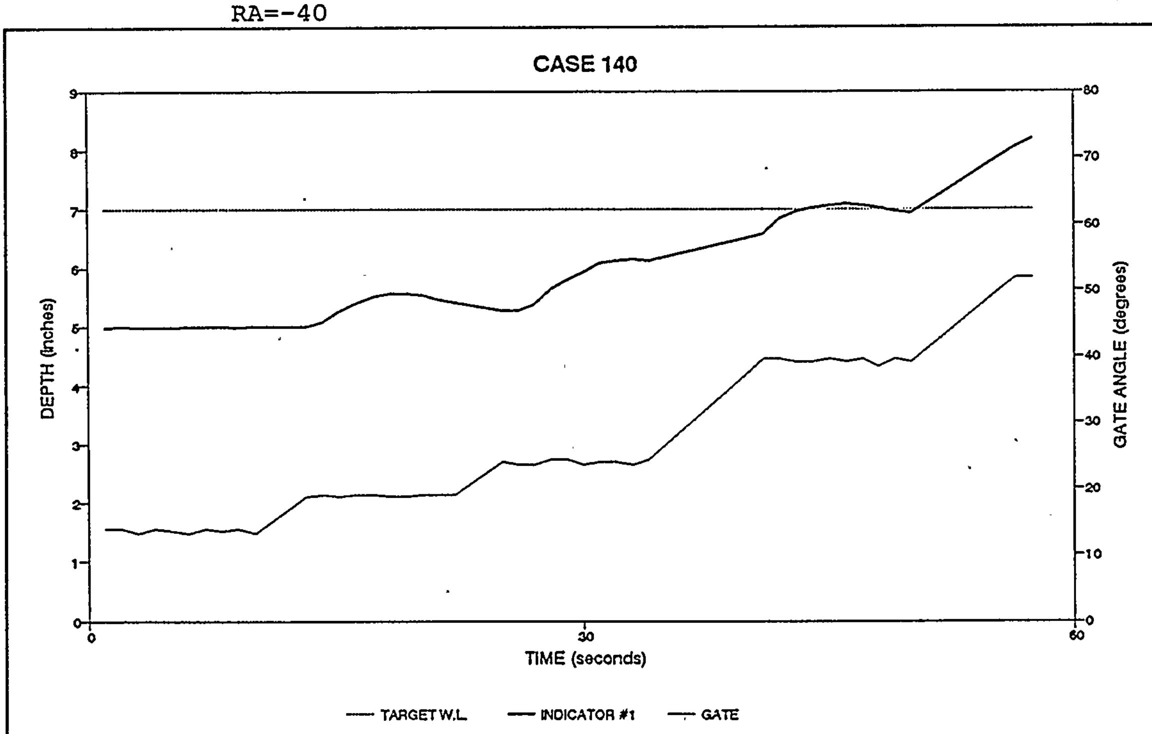


Figure 7.40 - PD Control, CASE 140
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.5; RA=-80

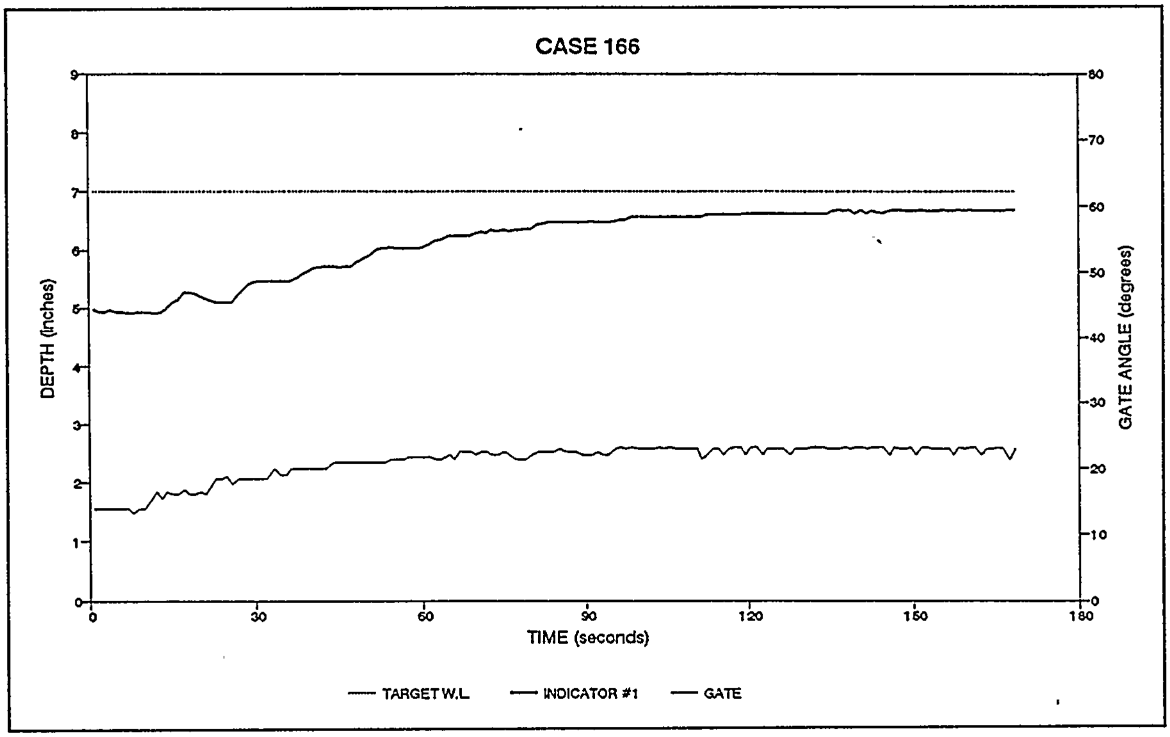


Figure 7.41 - PD Control, CASE 166
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.; DB=0.1 in.; K=0.25;
RA=-10

proportional correction is small to begin with, derivative action is not warranted. Although no cases were conducted using K>0.5, it is expected that derivative action would prove to be more useful because the proportional correction would be large.

7.5 PID Control

Table 7.5 summarizes the parameters and operating conditions tested, and Figures 7.42 to 7.69 are the plotted results of some key PID control cases tested. A number of other cases were conducted using positive values of RA, but as explained in the previous section they are not appropriate. Therefore, those cases are not included in this discussion.

Cases 141 to 177 and 217 to 220 were aimed at testing PID control using various combinations of TW and control parameters, to determine optimum values of each. Figures 7.42 to 7.54 illustrate their typical response characteristics. For reasons similar to that in Section 7.3, values of K larger than 0.5 were not tested. Generally, control cases using K=0.25 exhibited a flatter response characteristic than K=0.5, with less pronounced localized transients. However, the latter provided a more rapid response to set point or flow rate changes. The parameters RE and RA could, however, be selected so that the characteristics of K=0.25 closely resembled that of K=0.5.

It was determined that the following relationships provided good results using PID control:

Table 7.5 - Summary of Case Studies for PID Control

Case No.	Valve	TW (sec.)	ΔSP (in.)	DB (in.)	K	RE	RA
141	3.0	10	2	0.1	0.5	500	-5
142	3.0	10	2	0.1	0.5	500	-10
143	3.0	10	2	0.1	0.5	500	-20
144	3.0	10	2	0.1	0.5	500	-40
145	3.0	10	2	0.1	0.5	200	-5
146	3.0	10	2	0.1	0.5	200	-10
147	3.0	10	2	0.1	0.5	200	-20
148A	3.0	10	2	0.1	0.5	200	-40
150	3.0	10	2	0.1	0.25	250	-5
151	3.0	10	2	0.1	0.25	250	-2.5
152	3.0	10	2	0.1	0.25	250	-10
153	3.0	10	2	0.1	0.25	250	-20
154	3.0	10	2	0.1	0.25	250	-40
155	3.0	10	2	0.1	0.25	100	-2.5
156	3.0	10	2	0.1	0.25	100	-5
157	3.0	10	2	0.1	0.25	100	-10
158	3.0	10	2	0.1	0.25	100	-20
159	3.0	10	2	0.1	0.25	50	-2.5
160	3.0	10	2	0.1	0.25	50	-5
161	3.0	10	2	0.1	0.25	50	-10
162	3.0	10	2	0.1	0.25	50	-20
163	3.0	10	2	0.1	0.25	50	-40
168	3.0	20	2	0.1	0.25	100	-40
169	3.0	20	2	0.1	0.25	200	-40
170	3.0	20	2	0.1	0.5	200	-40
171	3.0	20	2	0.1	0.5	200	-20
172	3.0	20	2	0.1	0.5	400	-20
173	3.0	40	2	0.1	0.25	400	-80

Table 7.5 (con't.)

Case No.	Valve	TW (in.)	ΔSP (in.)	DB (in.)	K	RE	RA
174	3.0	40	2	0.1	0.25	800	-80
175	3.0	40	2	0.1	0.25	600	-80
176	3.0	40	2	0.1	0.5	1200	-40
177	3.0	40	2	0.1	0.5	1600	-30
178	2.0	10	2	0.1	0.25	100	-20
179	2.0	10	2	0.1	0.25	150	-20
180	2.0	10	2	0.1	0.5	300	-10
181	2.0	10	2	0.1	0.5	200	-10
182	2.0	20	2	0.1	0.25	300	-40
183	2.0	20	2	0.1	0.5	600	-20
184	5.0	10	2	0.1	0.25	100	-20
185	5.0	10	2	0.1	0.25	50	-20
186	5.0	10	2	0.1	0.5	200	-10
187	5.0	10	2	0.1	0.5	100	-10
188	10.0	10	2	0.1	0.25	100	-20
189	10.0	10	2	0.1	0.25	50	-20
190	10.0	10	2	0.1	0.5	200	-10
191	10.0	10	2	0.1	0.5	100	-10
192	3.0	10	1	0.1	0.25	100	-20
193	3.0	10	1	0.1	0.5	200	-10
194	3.0	10	4	0.1	0.25	100	-20
195	3.0	10	4	0.1	0.5	200	-10
196	3.0	10	4	0.1	0.5	300	-10
197	3.0	10	4	0.1	0.5	500	-10
198	3.0	10	2	0.1	0.25	100	-20
199	3.0	10	2	0.05	0.25	100	-20
200	3.0	10	2	0.0	0.25	100	-20
201	3.0	10	2	0.25	0.25	100	-20

Table 7.5 (con't.)

Case No.	Valve	TW (sec.)	ΔSP (in.)	DB (in.)	K	RE	RA
202	3.0	10	2	0.5	0.25	100	-20
203	3.0	10	2	0.1	0.5	200	-10
204	3.0	10	2	0.0	0.5	200	-10
205	3.0	10	2	0.25	0.5	200	-10
206	3.0	10	2	0.5	0.5	200	-10
217	varies	10	0	0.1	0.25	100	-20
218	varies	20	0	0.1	0.25	200	-40
219	varies	10	0	0.1	0.5	200	-10
220	varies	20	0	0.1	0.5	400	-20

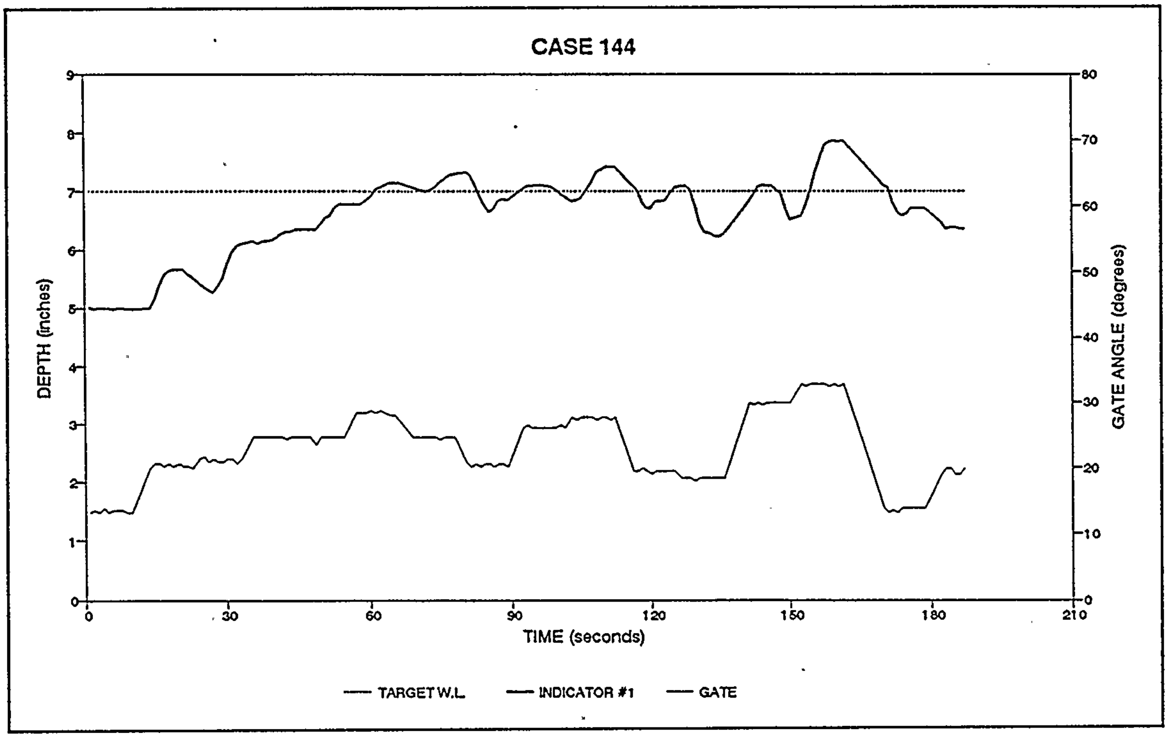


Figure 7.42 - PID Control, CASE 144
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5;
RE=500; RA=-40

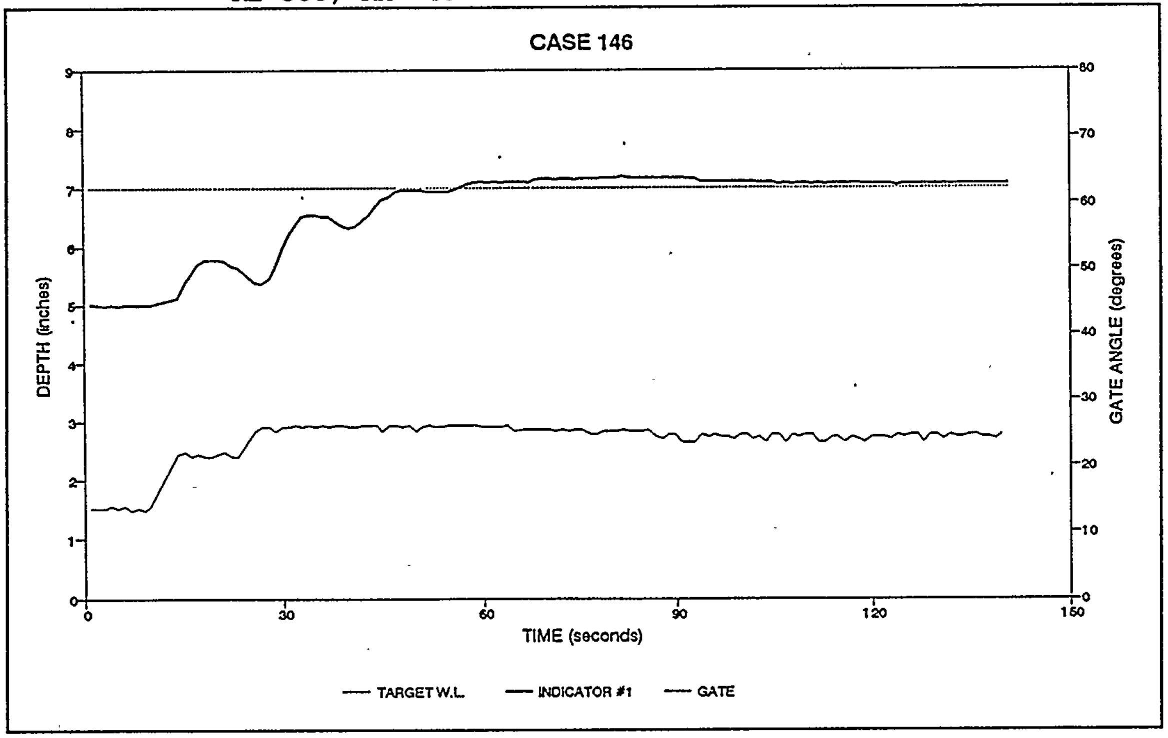


Figure 7.43 - PID Control, CASE 146
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5;
RE=200; RA=-10

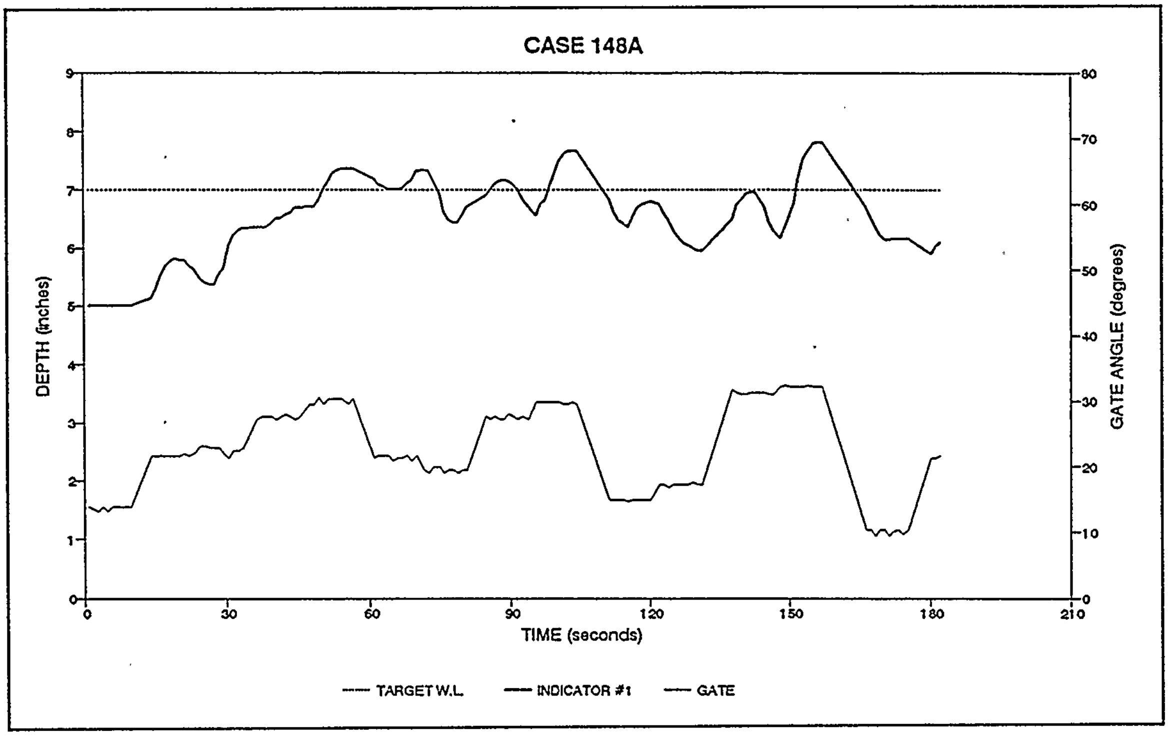


Figure 7.44 - PID Control, CASE 148A
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5; RE=200; RA=-40

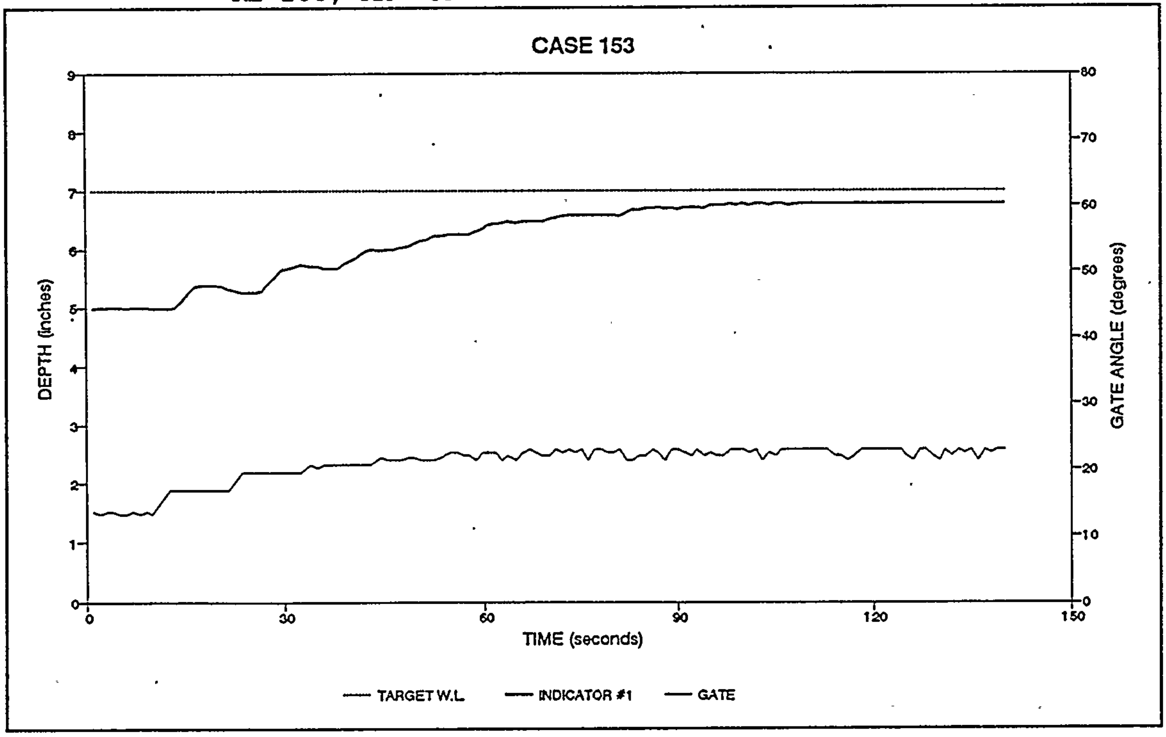


Figure 7.45 - PID Control, CASE 153
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.25; RE=250; RA=-20

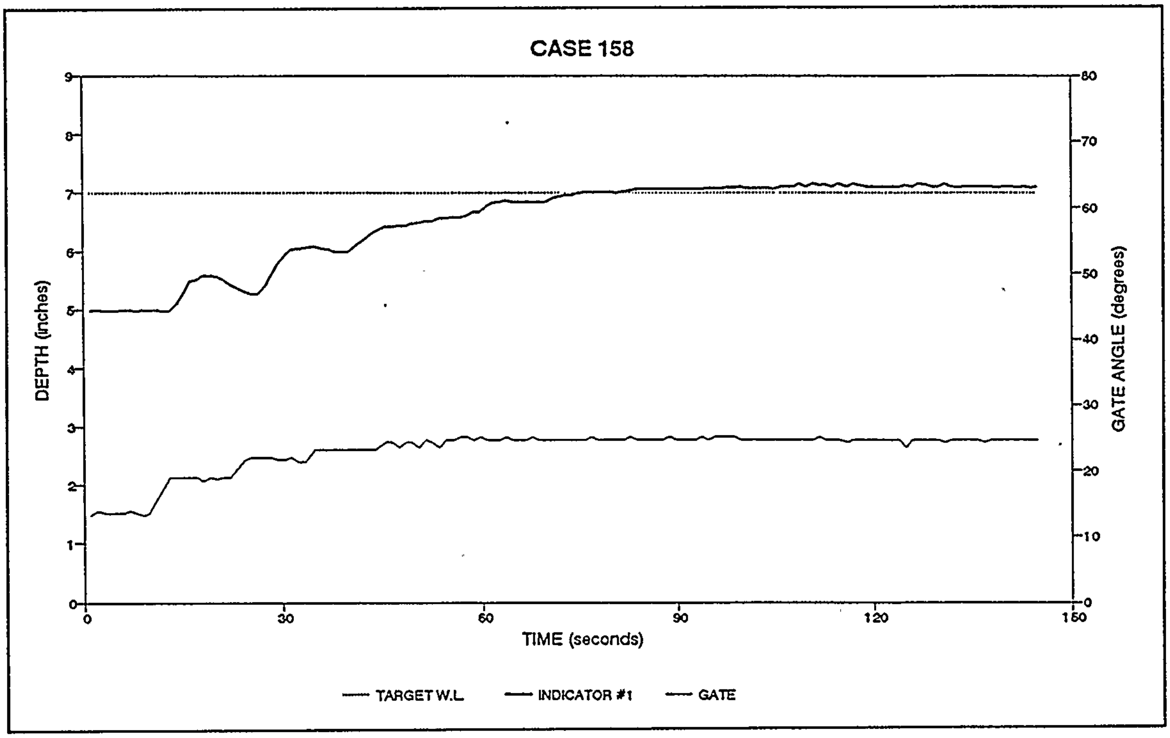


Figure 7.46 - PID Control, CASE 158
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.25; RE=100; RA=-20

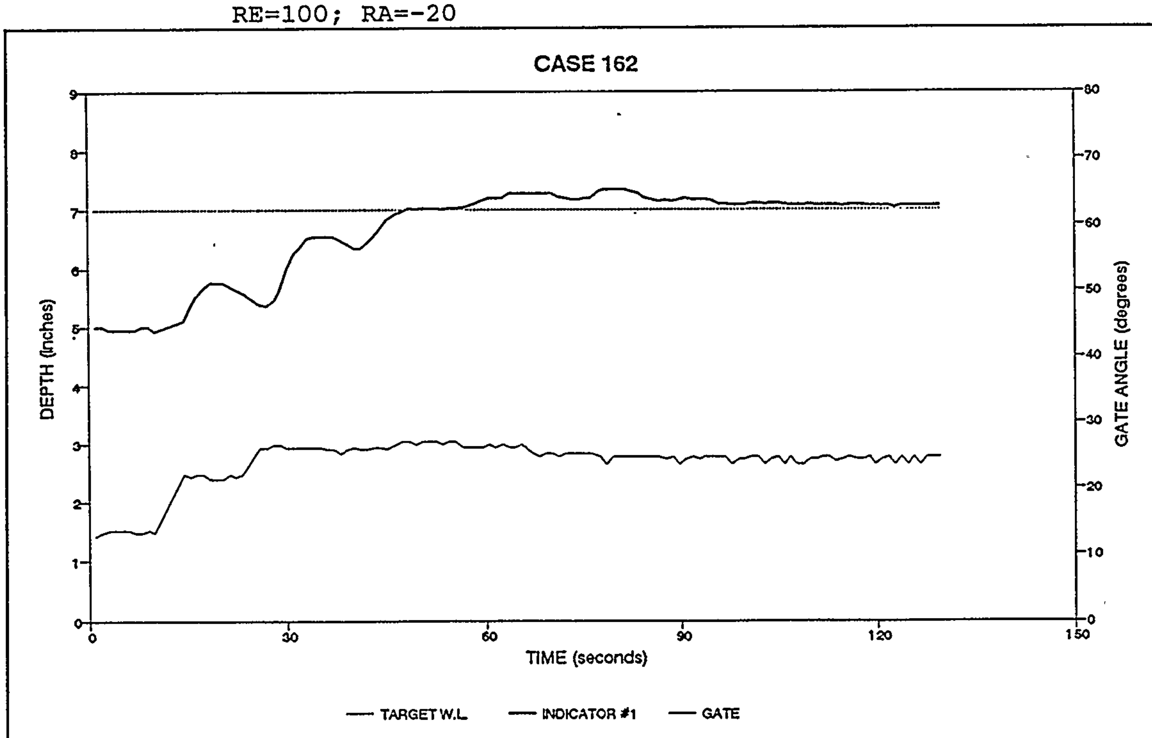


Figure 7.47 - PID Control, CASE 162
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.25; RE=50; RA=-20

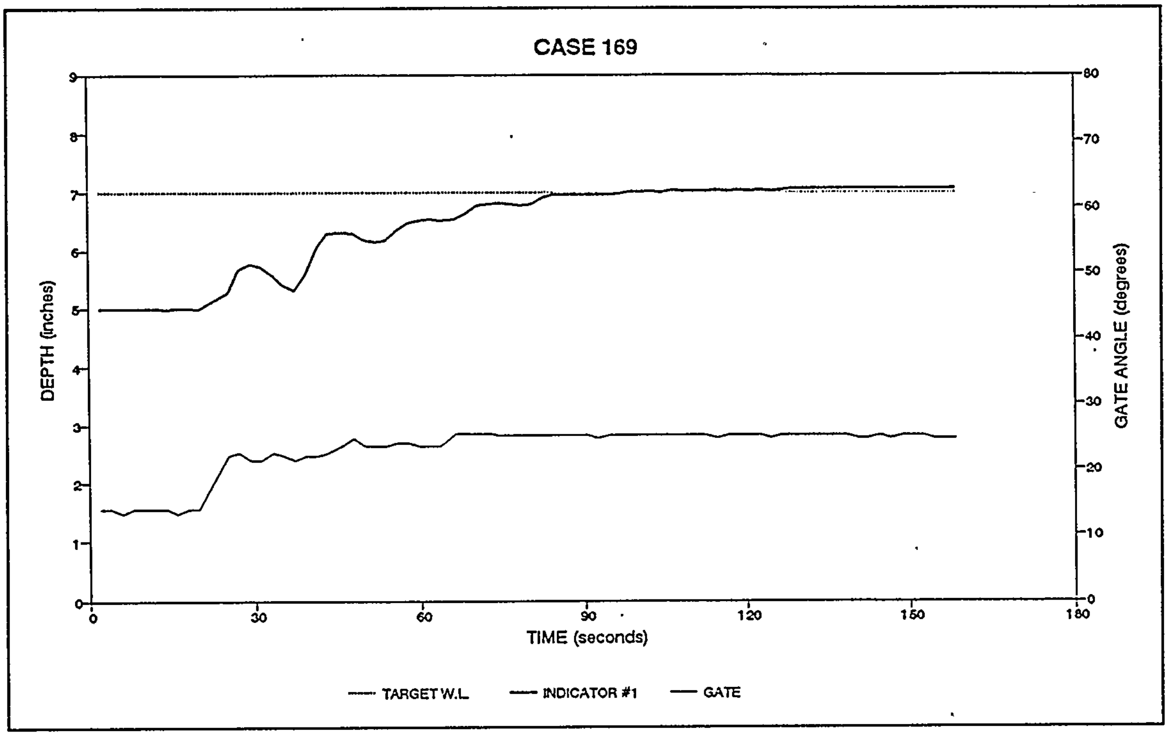


Figure 7.48 - PID Control, CASE 169
Valve @ 3.0; TW=20 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.25; RE=200; RA=-40

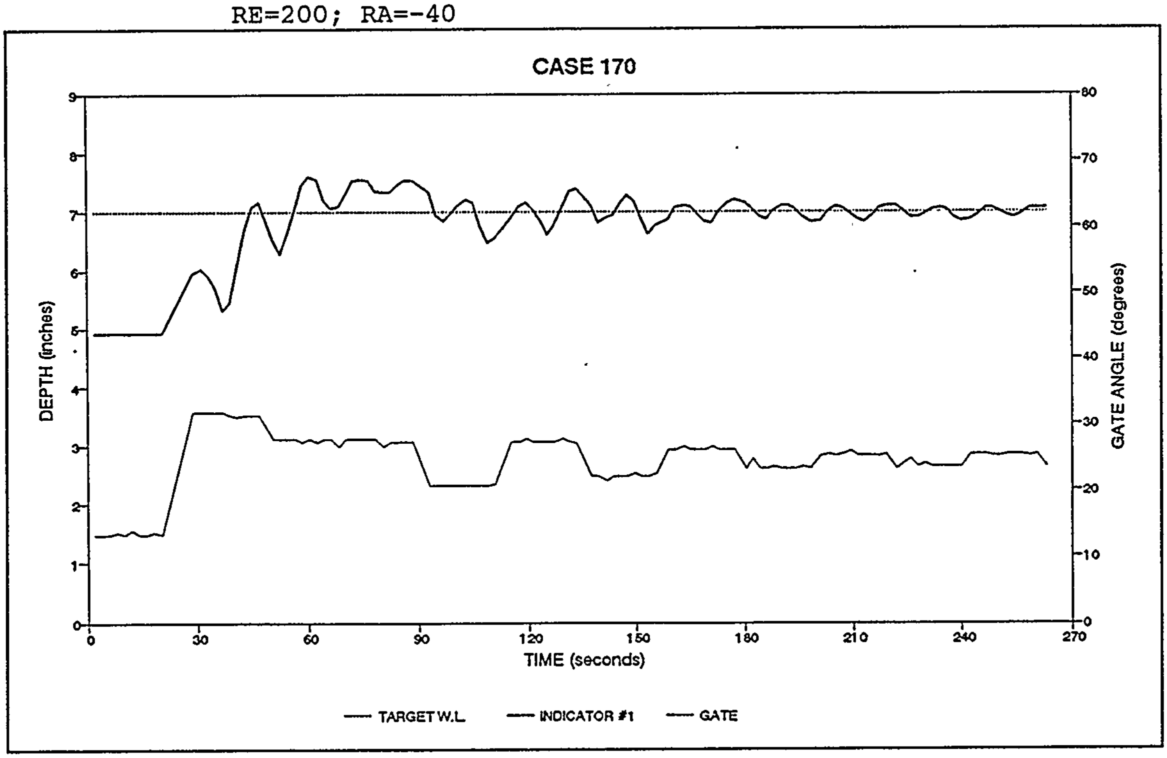


Figure 7.49 - PID Control, CASE 170
Valve @ 3.0; TW=20 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5; RE=200; RA=-40

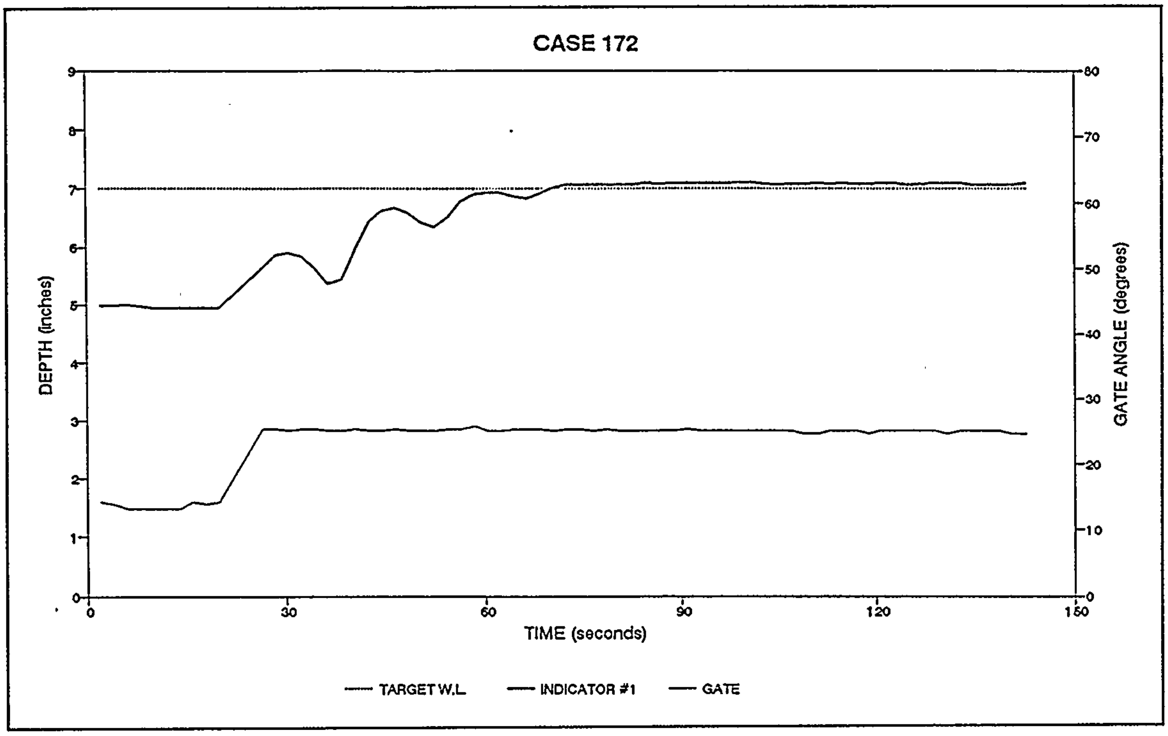


Figure 7.50 - PID Control, CASE 172
Valve @ 3.0; TW=20 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5; RE=400; RA=-20

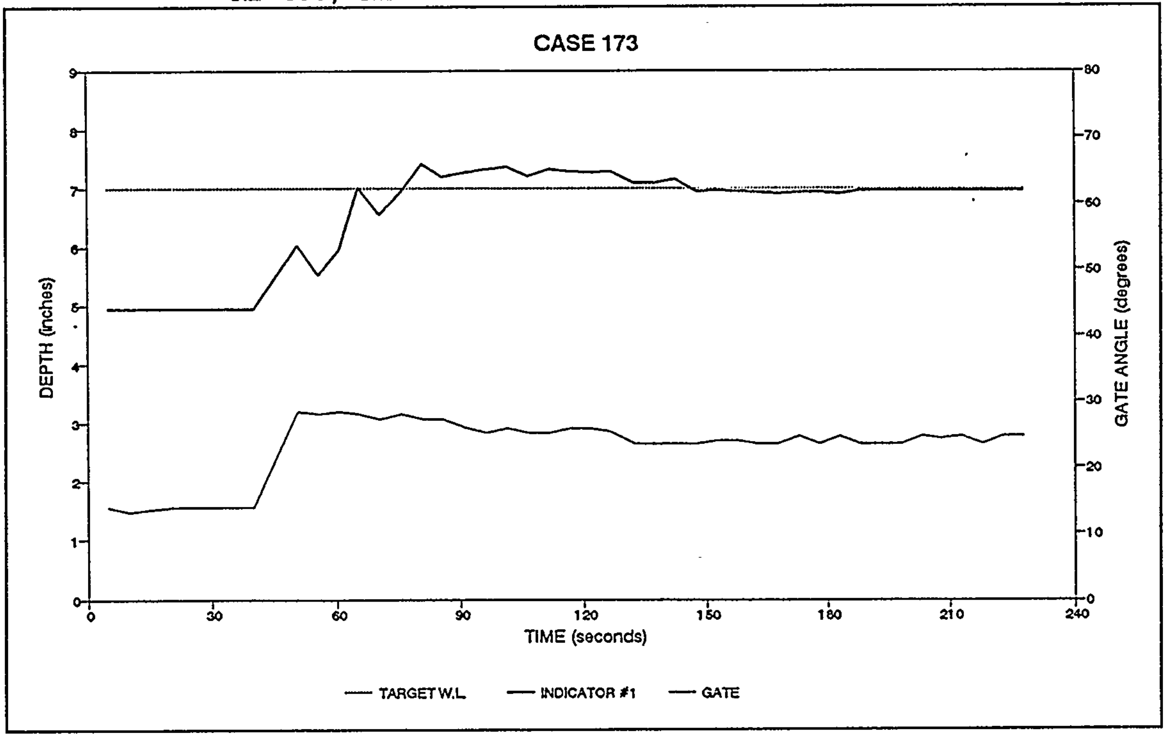


Figure 7.51 - PID Control, CASE 173
Valve @ 3.0; TW=40 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.25; RE=400; RA=-80

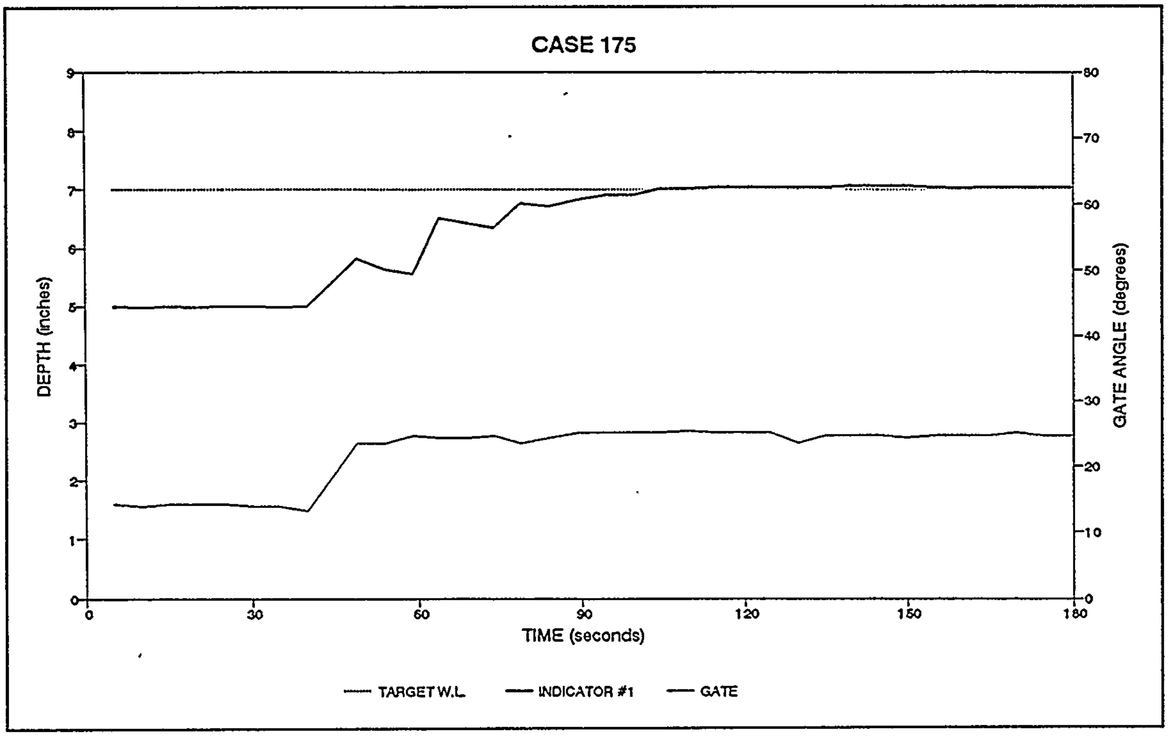


Figure 7.52 - PID Control, CASE 175
Valve @ 3.0; TW=40 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.25; RE=600; RA=-80

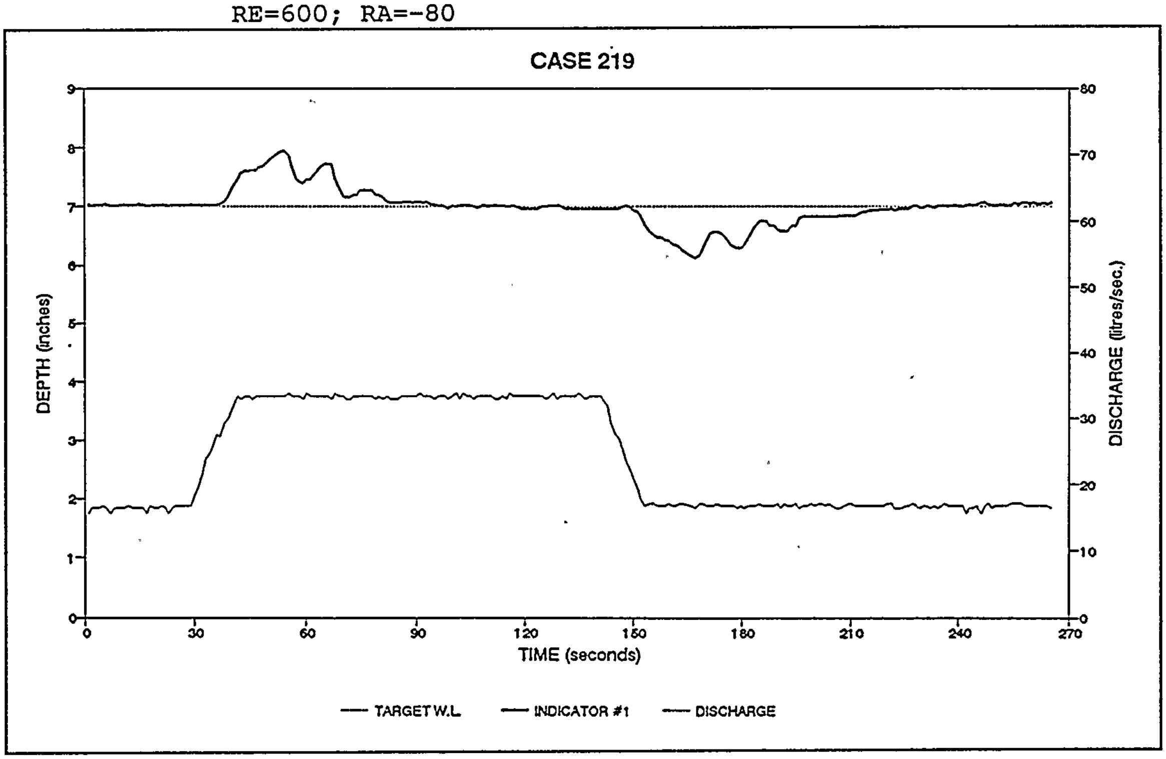


Figure 7.53 - PID Control, CASE 219
Q varies; TW=10 sec.; DB=0.1 in.; K=0.5; RE=200; RA=-10

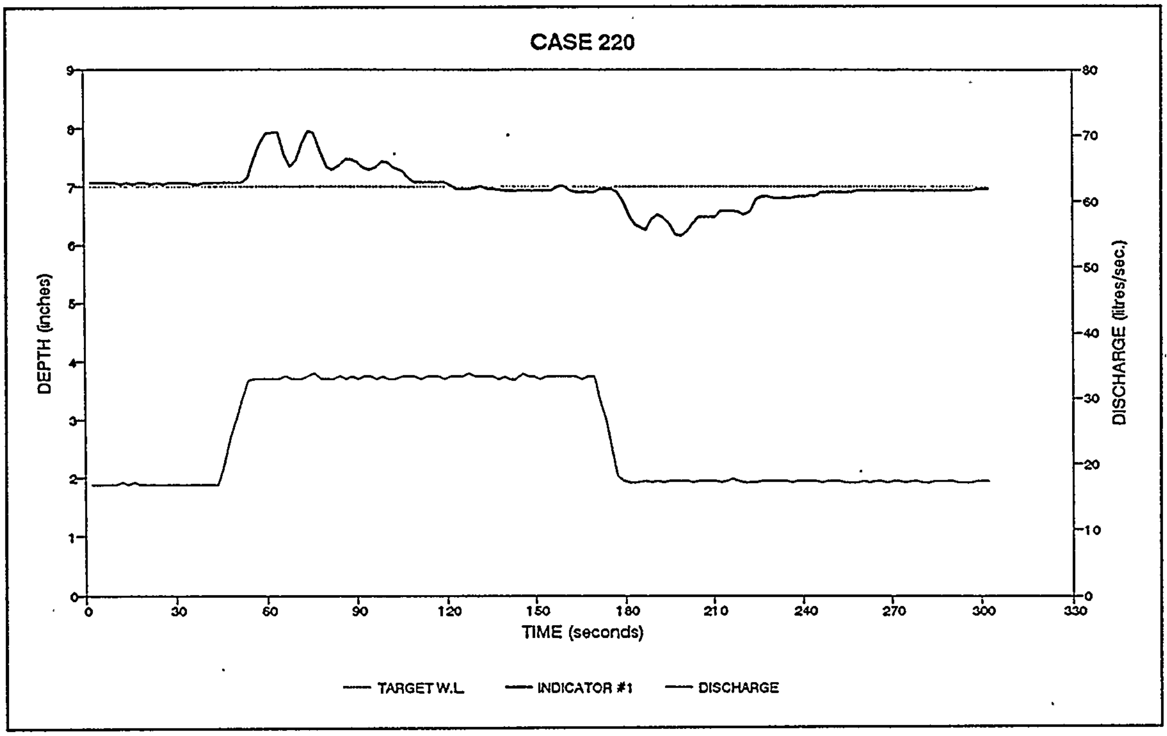


Figure 7.54 - PID Control, CASE 220
Q varies; TW=20 sec.; DB=0.1 in.; K=0.5; RE=400; RA=-20

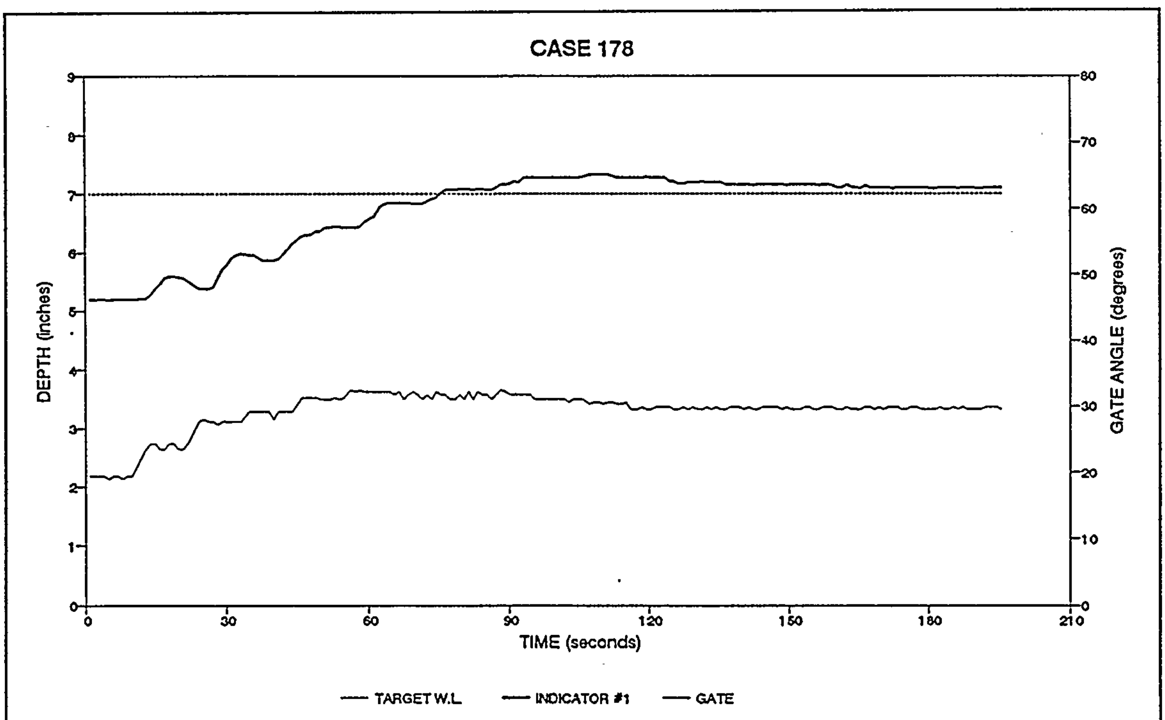


Figure 7.55 - PID Control, CASE 178
Valve @ 2.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.25; RE=100; RA=-20

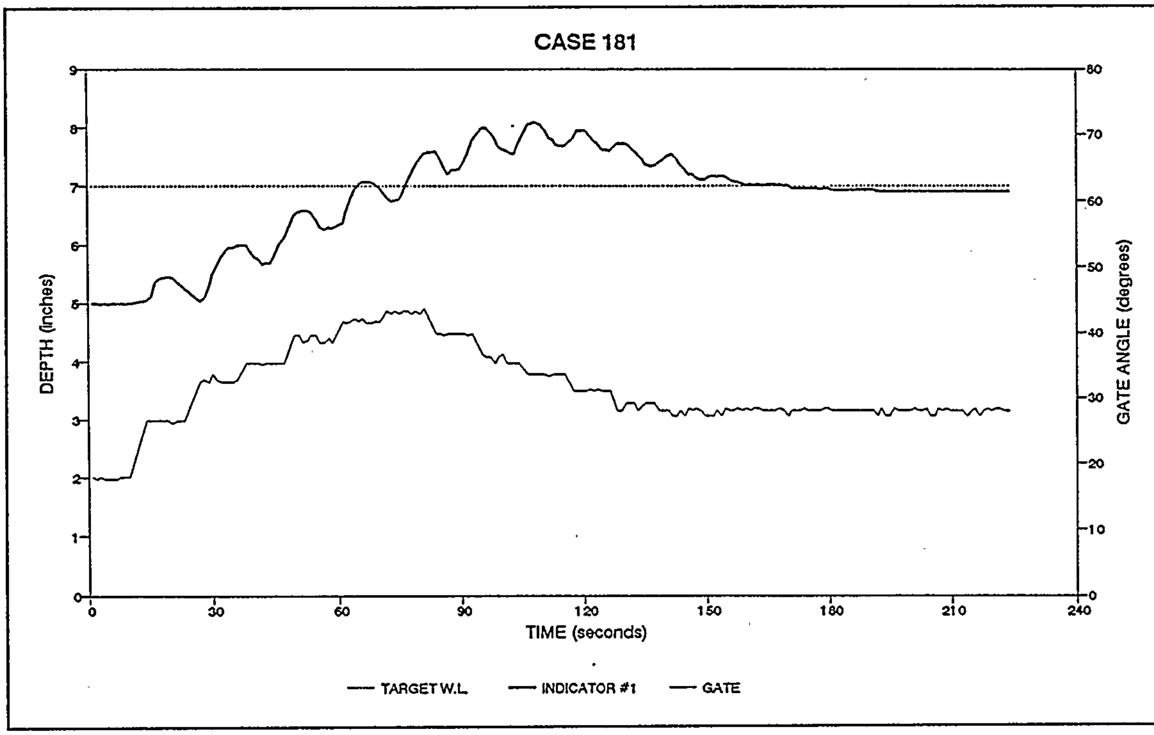


Figure 7.56 - PID Control, CASE 181
Valve @ 2.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5;
RE=200; RA=-10

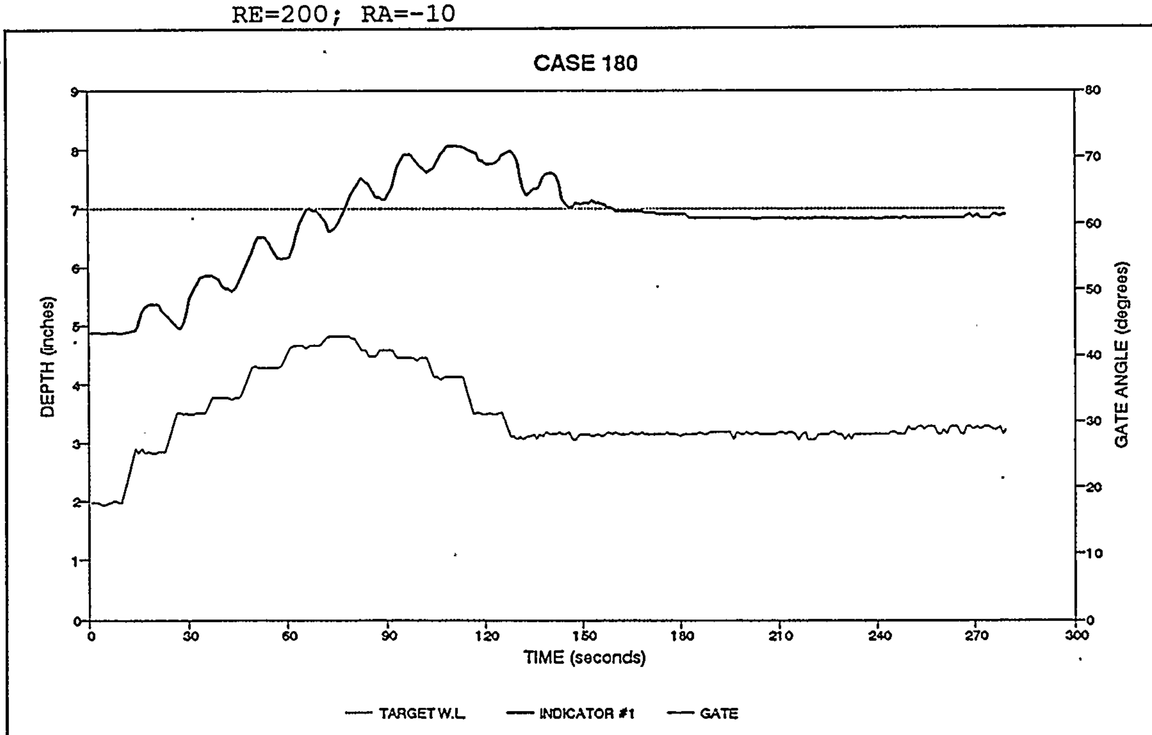


Figure 7.57 - PID Control, CASE 180
Valve @ 2.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5;
RE=300; RA=-10

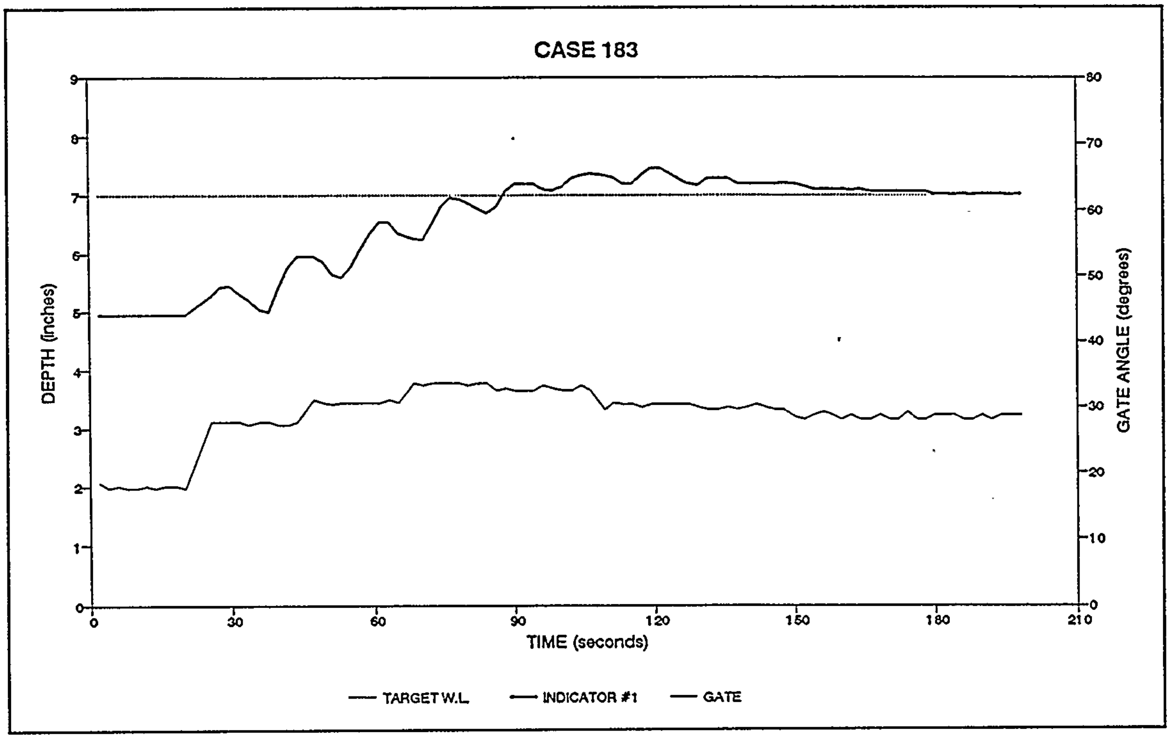


Figure 7.58 - PID Control, CASE 183
Valve @ 2.0; TW=20 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5; RE=600; RA=-20

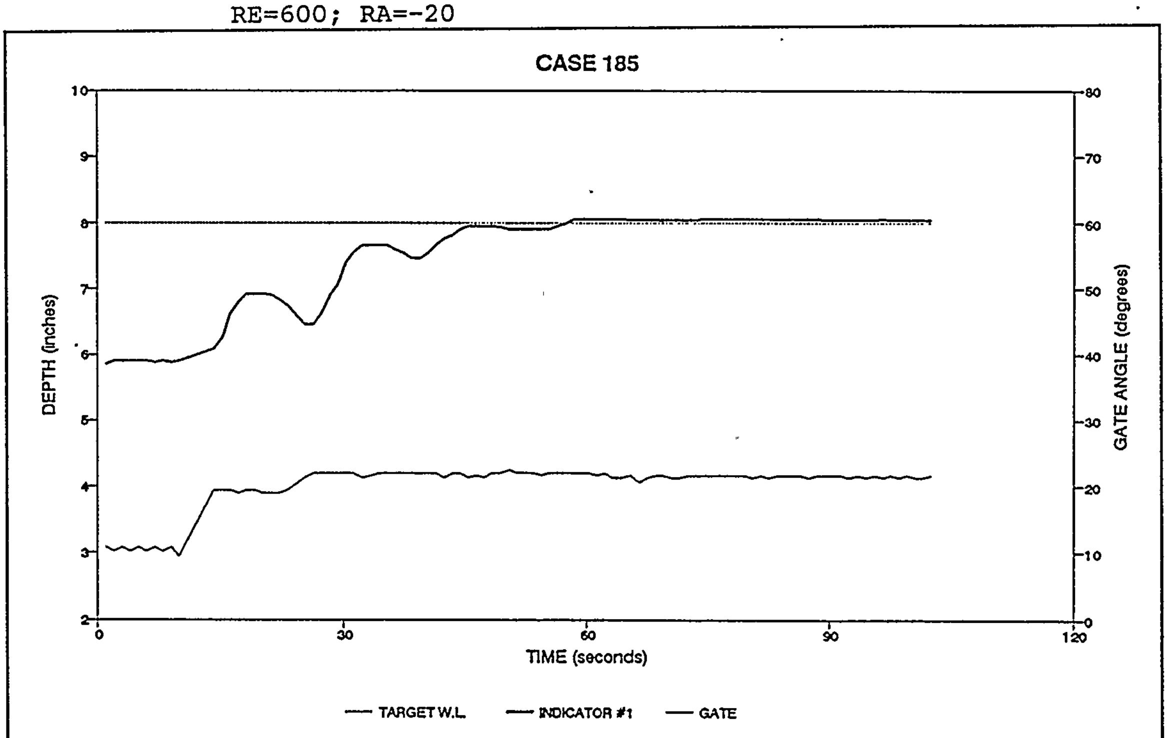


Figure 7.59 - PID Control, CASE 185
Valve @ 5.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.25; RE=50; RA=-20

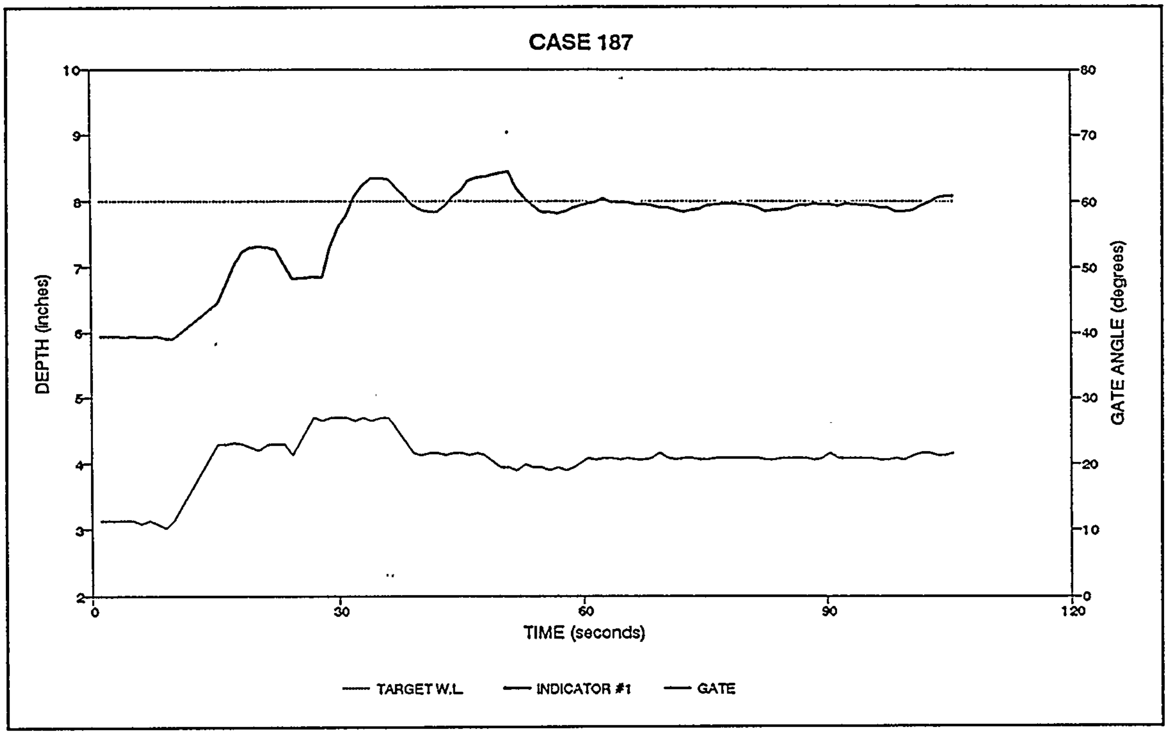


Figure 7.60 - PID Control, CASE 187
Valve @ 5.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5;
RE=100; RA=-10

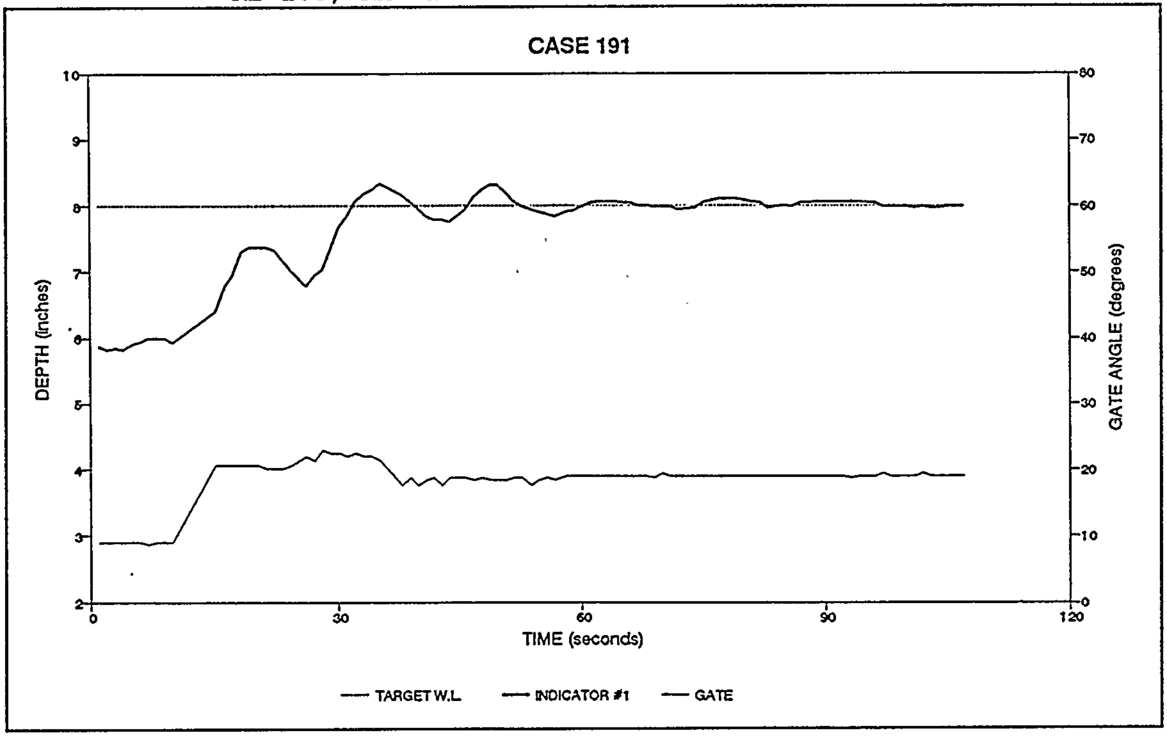


Figure 7.61 - PID Control, CASE 191
Valve @ 10.0; TW=10 sec.; ΔSP=2 in.;DB=0.1 in.; K=0.5;
RE=100; RA=-10

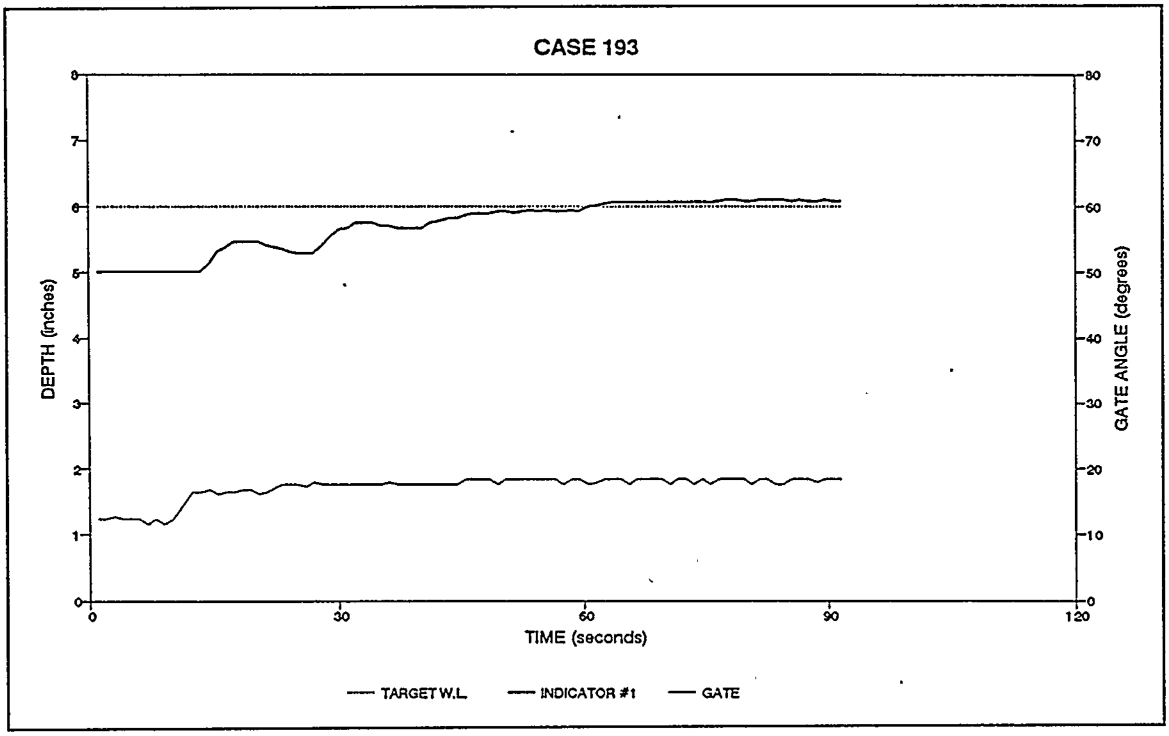


Figure 7.62 - PID Control, CASE 193
Valve @ 3.0; TW=10 sec.; ΔSP=1 in.;DB=0.1 in.; K=0.5;
RE=200; RA=-10

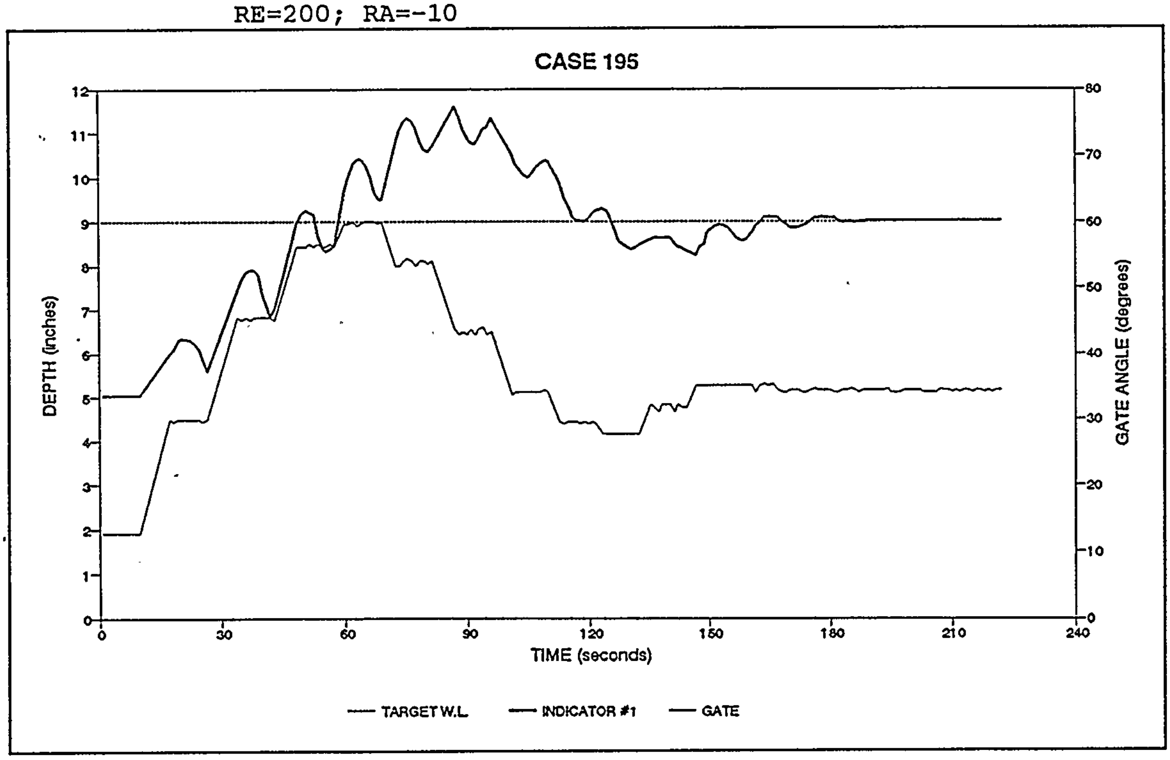


Figure 7.63 - PID Control, CASE 195
Valve @ 3.0; TW=10 sec.; ΔSP=4 in.;DB=0.1 in.; K=0.5;
RE=200; RA=-10

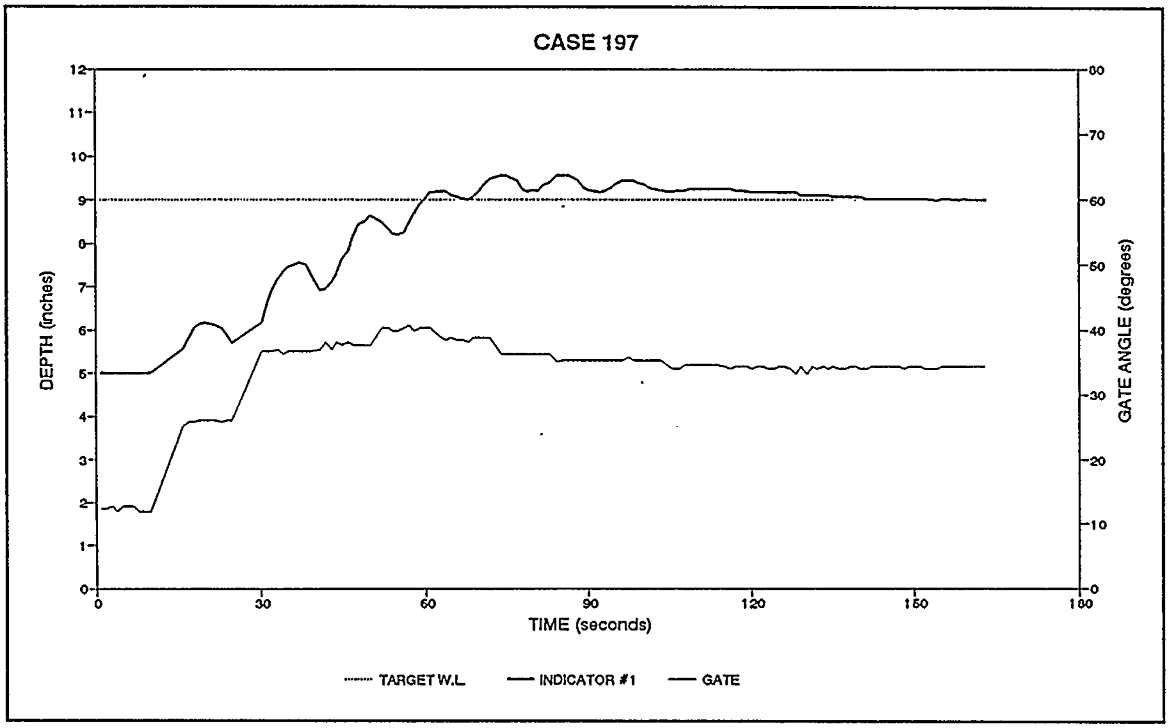


Figure 7.64 - PID Control, CASE 197
Valve @ 3.0; TW=10 sec.; ΔSP=4 in.;DB=0.1 in.; K=0.5;
RE=500; RA=-10

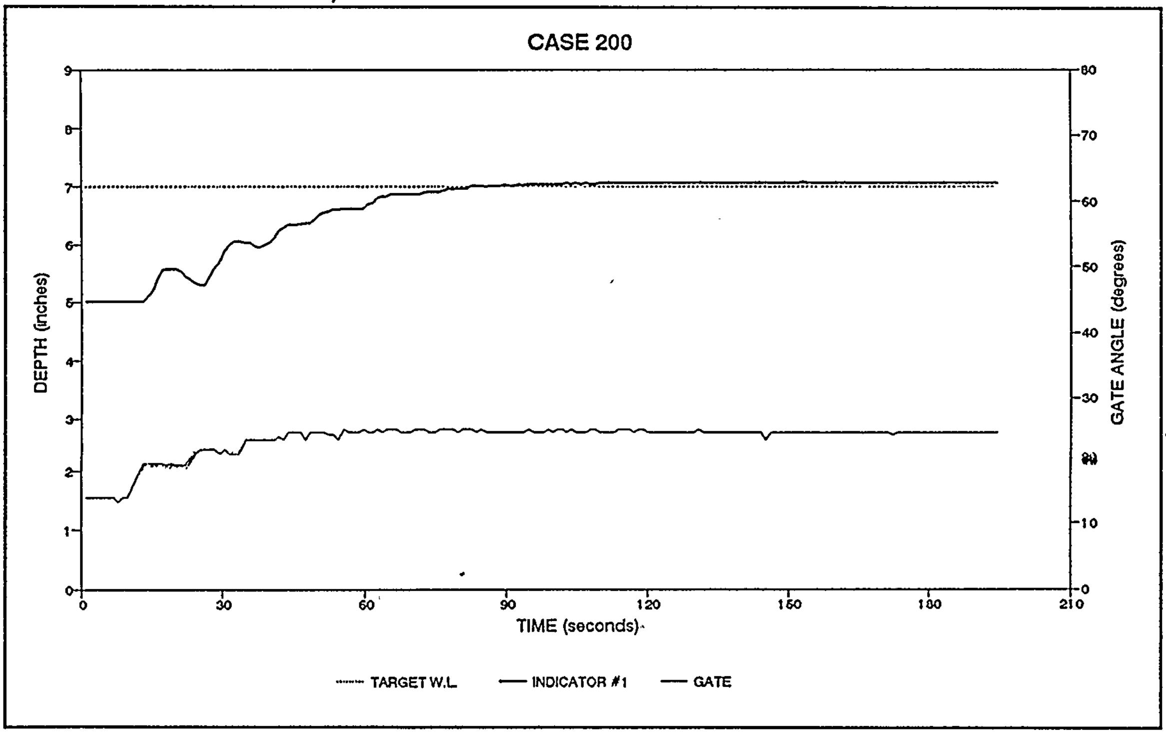


Figure 7.65 - PID Control, CASE 200
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.0 in.; K=0.25;
RE=100; RA=-20

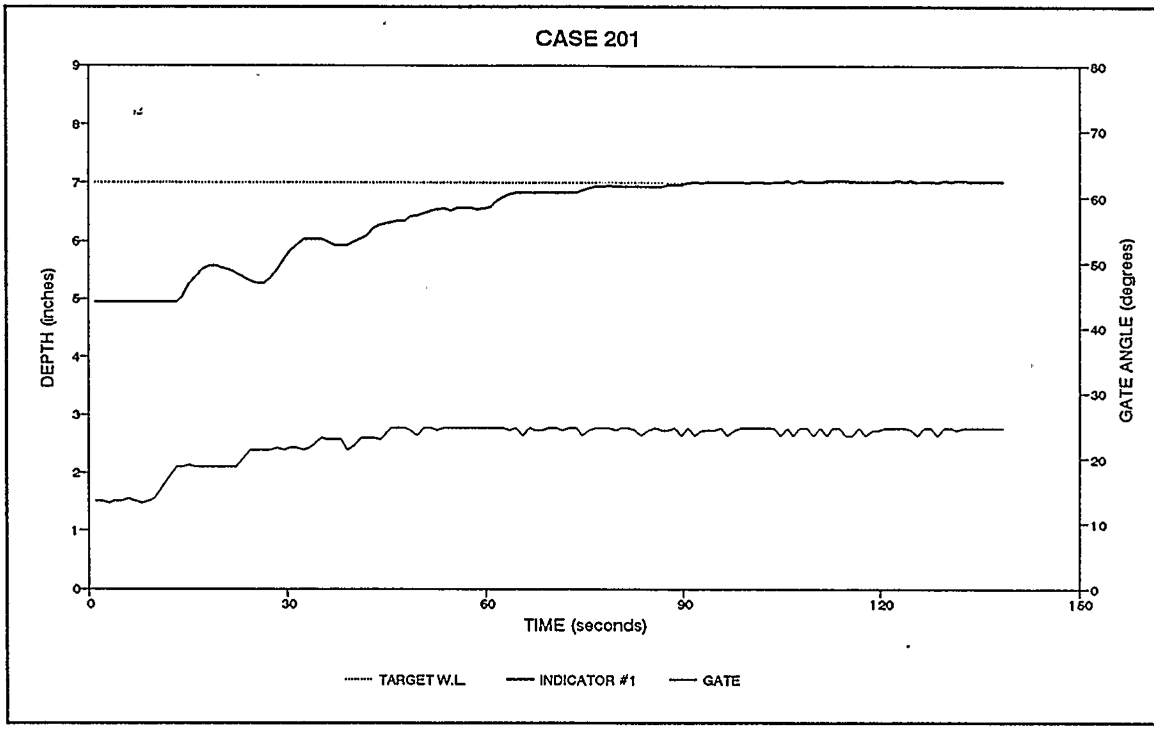


Figure 7.66 - PID Control, CASE 201
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.25 in.; K=0.25;
RE=100; RA=-20

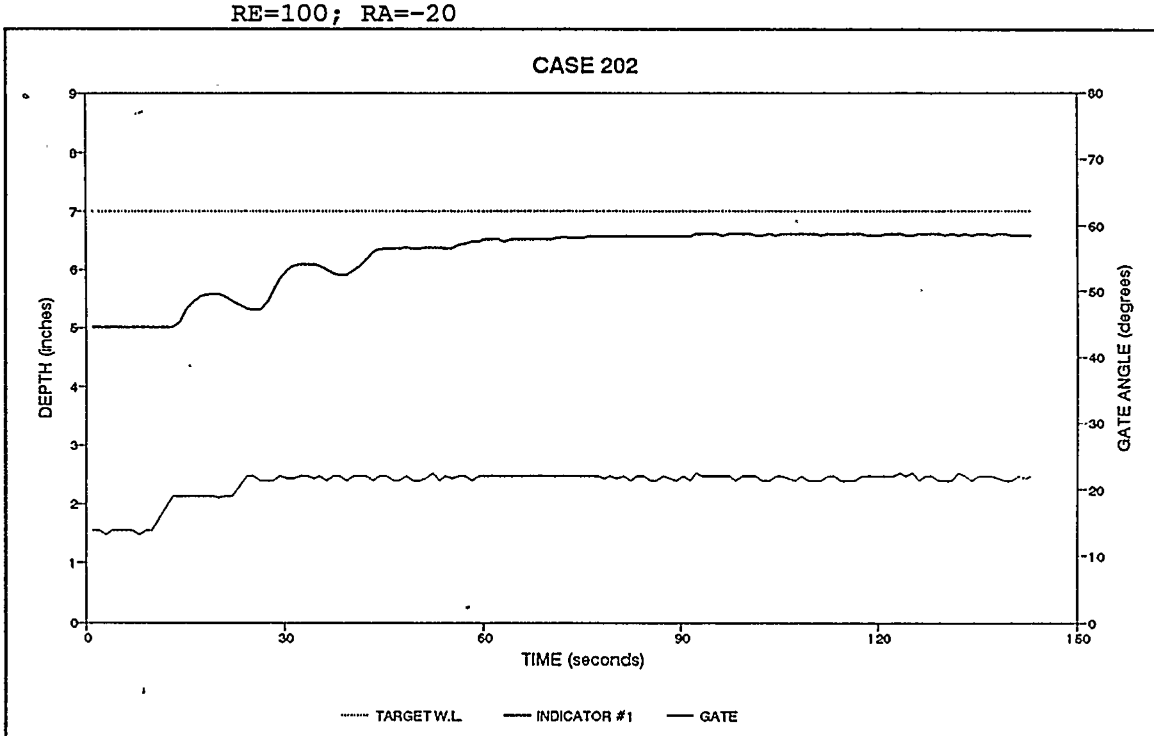


Figure 7.67 - PID Control, CASE 202
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.5 in.; K=0.25;
RE=100; RA=-20

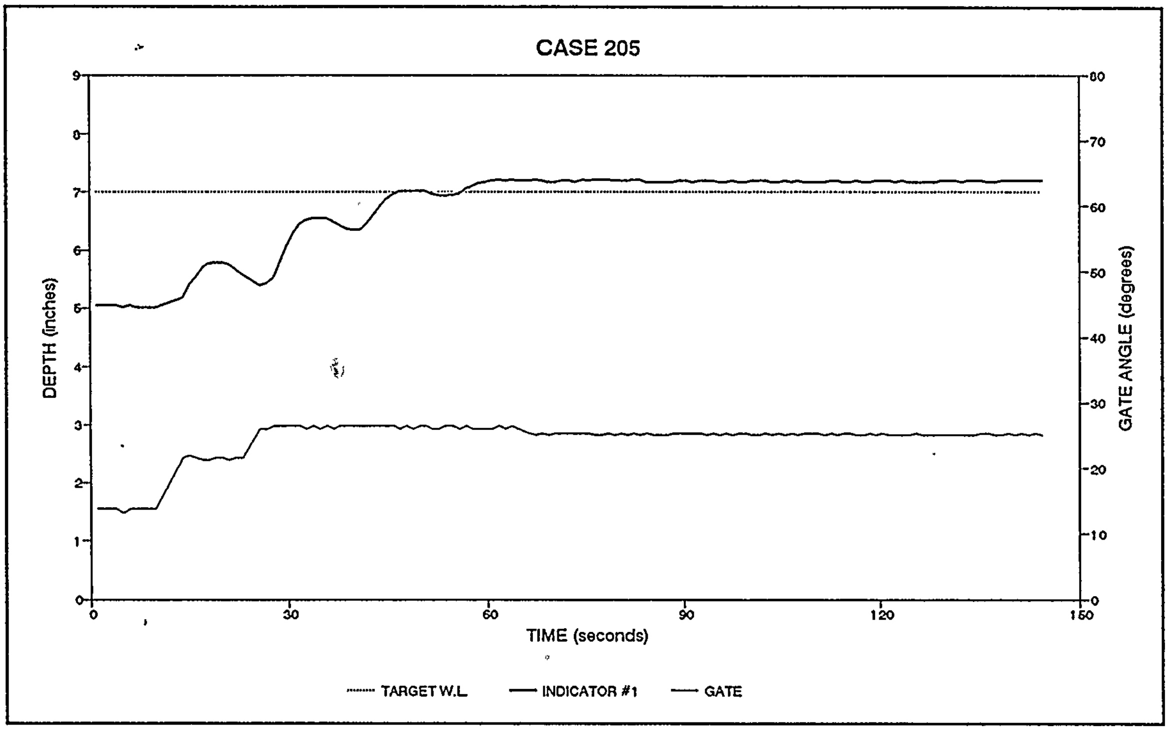


Figure 7.68 - PID Control, CASE 205
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.25 in.; K=0.5; RE=200; RA=-10

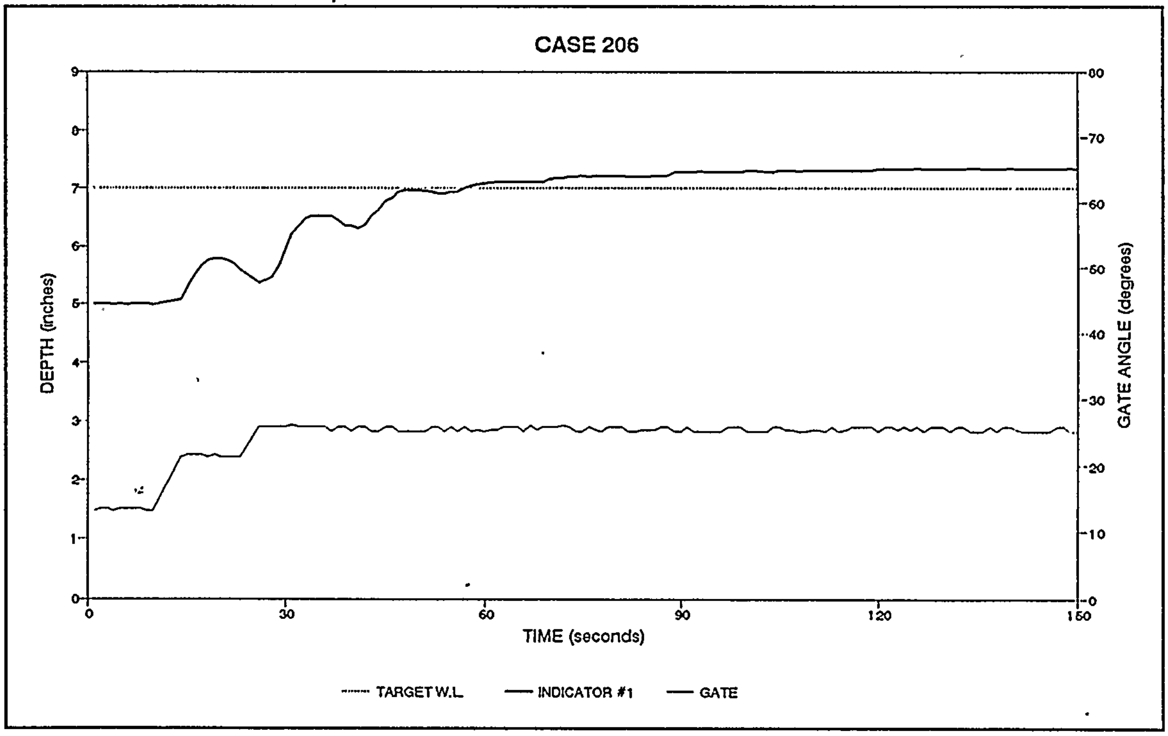


Figure 7.69 - PID Control, CASE 206
Valve @ 3.0; TW=10 sec.; ΔSP=2 in.;DB=0.5 in.; K=0.5; RE=200; RA=-10

$$\frac{K(TW)}{RE} \approx 0.025$$

$$\frac{K(RA)}{TW} \approx -0.5$$

The characteristics, which are illustrated by Figures 7.43, 7.46, 7.48, 7.50, 7.51, 7.53 and 7.54, are initial rapid response to a set point or flow rate change, followed by adequate damping to quickly stabilize the water level (no more than ½ cycle).

Lower values of K(TW)/RE provided a flatter response. This was only considered an improvement when TW was 40 seconds (Figure 7.52). Larger values of 0.05 were used with K=0.25 (Figure 7.47) and yielded good results. However, if RE was too large, and using K=0.25, then steady state error resulted (Figure 7.45).

Because integral action was included, higher values of RA could be used than with just PD control. However, as K(RA)/TW approached -1 (Figure 7.49), instability started. Figures 7.42 and 7.44 show high instability at K(RA)/TW=-2, in which the gate movement steadily increased in magnitude.

Larger values of TW caused slightly longer times until the water level stabilized about the set point. As discussed previously in Section 7.1, this is only an important consideration when the set point is constant and large fluctuations in level cannot be tolerated for very long. Additionally, the longer TW values reduced the number of gate adjustments required. This can be illustrated by comparing Figures 7.46, 7.48 and 7.51 to each other, where TW=10, 20 and 40 seconds respectively.

Cases 178 to 191 (Figures 7.55 to 7.61) tested the sensitivity of the gate and control algorithm to set point changes for different flow rates. Previous set point change cases were conducted at valve setting 3.0, which represented a flow rate of about 15 l/s, or approximately 38% capacity. These new cases were done using valve settings 2.0, 5.0 and 10.0 which represent approximately 13%, 82% and 100% capacities respectively. To provide a basis for comparison, the above relationships for K(TW)/RE and K(RA)/TW were used as starting points.

At the lower flow rate (Figures 7.55 to 7.58) best performance was achieved using K=0.25 (Figure 7.55). With cases using K=0.5 the number of gate adjustments and time to stabilization increased dramatically (Figure 7.56). Even increasing the value of RE did not significantly improve the response (Figure 7.57). Increasing TW to 20 seconds reduced the number of gate adjustments and which provided the response sought (Figure 7.58).

This characteristic to a very low flow rate was not unexpected. The response in water level to a gate movement or correction was much slower, hence the derivative term was less effective and easily overpowered by integral and/or large proportional actions. During the longer waiting time periods the overall change in water level was greater, so the required corrections were reduced. Regardless of the final parameters necessary to provide optimum response, the total time to steady state condition was longer.

At the higher flow rates (Figures 7.59 to 7.61) the water level responded much quicker to gate adjustments. This made it possible to reduce RE and provide a faster time to stabilize the water level about the target. Values of K(TW)/RE=0.05 were used without adversely affecting the response characteristics. Fewer gate adjustments were required than with the lower flow rates. Also, the wave disturbances caused by the gate movements were less pronounced

Cases 192 to 197 (Figures 7.62 to 7.64) tested the sensitivity of the gate and control algorithm to set point change situations, using smaller and larger values of ΔSP than previous. When ΔSP=1 in. (Figure 7.62), adjustments were smaller and water level response was smoother than with ΔSP=2 in. (Figure 7.43). Also, localized transients were reduced. With ΔSP=4 in. (Figures 7.63), more adjustments were made and cycling increased, particularly at K=0.5. Also, wave disturbances were more pronounced. For the larger ΔSP, it was necessary to increase RE so that the water level response was smoother (Figure 7.64; K(TW)/RE=0.01).

Up to now all cases were conducted using a deadband (DB) of 0.1 in. The sensitivity of DB was tested by Cases 198 to 206 (Figures 7.65 to 7.69). As with all previous cases of PD and PI control, the control program compared DB to the total correction rather than the error. It was shown previously that this is difference in philosophy was not significant if integral action was included, or if K was large enough when only P control was used.

When K=0.25 there was little difference between the target and final water level achieved for DB up to 0.25 in. (Figure 7.66). However, at low DB values of 0.05 or 0.0 in. (Figure 7.65) the gate made frequent minute adjustments, without visibly altering the water level. These adjustments are not easily visible by inspecting the plotted results, but they are apparent upon inspection of the printed data. This was similar when K=0.5, but there was a noticeable difference between target and final water level at DB=0.25 in. (Figure 7.68). In both cases when DB=0.5 in. (Figure 7.67 and 7.69), the steady state error was much more pronounced.

Except at the values of DB equal to or close to zero, there was no appreciable affect on the control action by changing DB. It primarily determined the accuracy to which the water level is established relative to the target. When K=0.25 the final water level was below the target, and when K=0.5 the final water level was above the target. This was not characteristic of these particular values, but rather it was coincidental of the control settings selected. The PID control parameters selected tended to undershoot the target when K=0.25 and overshoot it when K=0.5. This action could have been changed by refining the RE, RA or TW terms, but there was no reason to do so for the purpose of this project.

CHAPTER 8.0

DISCUSSION OF OBSERVATIONS

8.1 Control Performance

Floating (SOT/SRT), P, PI, PD and PID control methods provided suitable control of the pivoting overshot gate. The control parameters for each method could be altered to ensure acceptable operations. However, PID Control provided the most flexibility in designing gate response to either set point or flow rate changes.

Floating Control was the most simple type tested. Only one control parameter could be adjusted to affect gate response; the waiting time period (TW). This limited the control action of the gate to a singular type of water level response, and a high potential for cycling about the set point. Very high values of TW minimized cycling, but the response in upstream water level was slow. Proportional Control improved gate action to make it possible to eliminate cycling altogether, but water level response was even slower. Also, frequent gate adjustments were required. As K approached 1.0, P Control resembles Floating Control. When K approached zero, response was slow and steady state error occurred.

Proportional Control provided the flattest water level response curve and reduced both local transients and cycling about the set point. With low values of K, steady state error resulted. This is characteristic of this type of control, as reported in the literature.

Adding integral action to P Control caused large gate adjustments to be made when the error was sustained over time (slow water level response), and small adjustments as the error decreased. Overall, the water level response resembled that of Floating Control, but it was faster. During initial adjustments the error was either large to begin with (set point change) or grew in magnitude (flow rate change). Consequently gate adjustments were dominated by integral correction. As the water level approached the set point the integral action diminished and proportional correction dominated. Instability would quickly occur if the reset time (RE) was too small.

Derivative action dampened gate adjustments in proportion to the change in water level. However, it easily caused instability if the absolute value of the rate gain (RA) was too large. Adding derivative action to P Control made it possible to utilize larger values of K, but the response closely resembled P Control. It is the opinion of this author that PD Control is not an improvement over P Control, that the RA parameter adds a level of complexity that is not warranted.

Derivative action was most effective with PID control. While PI Control tended to cycle, derivative action anticipated water level response and dampened gate adjustments. This made it possible to achieve rapid water level response without causing cycling. The decision making process simulated by PID Control provided the most flexibility in automatic gate control.

Water level response lagged gate movements because of channel storage and wave travel speed. Low rates of flow exhibited a much slower response time, and control methods favouring proportional action were most effective. By contrast, high rates of flow responded to gate adjustments much faster, and control methods with high integral action provided rapid response characteristics.

8.2 Control Parameters

The small wave disturbances known as localized transients did not affect the control actions. However, the cycling motion of the water level about the set point, which is a higher level transient condition, was a factor in the performance of the control actions. When the cycling was eliminated, water level response was smooth and gate movements were minimized. When cycling increased, it caused the control actions to behave in a hunting fashion, in which the gate moved back and forth past the ultimately desired gate position. In extreme conditions of instability, the gate actions increased steadily until its physical capabilities were exceeded.

The following parameter adjustments, either individually or collectively, effectively reduced or eliminated cycling conditions:

Floating Control - increase TW

P Control - increase TW, decrease K

PI Control - increase TW, decrease K, increase RE

PD Control - increase TW, decrease K

PID Control - increase TW, decrease K, increase RE, increase absolute value of RA

Altering RA was less effective in reducing cycling than altering the other parameters. If its absolute value was increased too much, cycling conditions would worsen. This was particularly true without integral action included, and for this reason it is felt that altering RA is not an effective method of reducing cycling with PD Control.

Because of its influence on cycling with all control methods, the waiting time period (TW) proved to be a key parameter. Although larger values of TW reduced and eliminated cycling, they also resulted in longer periods of time to pass until steady state conditions were achieved. Also, during test cases for flow rate change (constant set point), the water level deviated further from the set point than it did with short durations of TW. Overall, values of TW=10 and 20 seconds provided good control responses, with a compromise between cycling and time to steady state conditions.

The rate of gate movement is another key element to the control action. If the winch used in this project raised and lowered the gate at a much slower rate, then the response characteristics would be much different. Since hydraulic transients were caused by gate movements, they would have been decreased or eliminated. If the gate responded slow enough all control methods would have behaved similar to SOT/SRT Floating Control.

Very slow gate movement is basically P Control with a small value of K. The case studies conducted using K=0.25 provide an example of the characteristics that could be expected.

On the otherhand, rapid gate movement provided quicker responses and shorter time to achieve steady state conditions. Fast gate movement does not present a difficult problem because the control parameters can be modified to simulate slower action if it is warranted.

The deadband was more importantly a factor of tolerance in upstream water level than it was a control parameter. The value used throughout most of the test cases represented less than 0.1% of the maximum water depth allowed, which resulted in reasonably accurate closure of the set point and water level. As the deadband approached 4% of the maximum depth, the deadband error became more pronounced. At lower values, the accuracy did not noticeably improve, but the number of minute gate movements markedly increased. Also, it did not seem to matter that the control program was structured to compare the total correction to the deadband rather than comparing the error to the deadband, except when P Control was used with K=0.25.

CHAPTER 9.0

CONCLUSIONS

All control methods tested provided good response characteristics to set point or flow rate change situations, but P, PI and PID Control are felt to be the most practical methods for controlling upstream water levels. In particular, PID Control provides the most flexibility in allowing the operator to regulate water levels for a variety of situations. This control most closely simulates decision making processes normally made in operating the pivoting overshot gate. The cost of this flexibility is that PID Control requires the most testing to determine optimum control parameter values.

Relationships between control parameters can be developed for a site specific installation that provide optimum control in upstream water level. For this project, the following provided the best response characteristics overall in terms of quick response time and minimum cycling, for P, PI or PID Control:

$$K=0.5$$

$$\frac{K(TW)}{RE}\approx 0.025$$

$$\frac{K(RA)}{TW}\approx -0.05$$

Rapid gate movement causes two forms of hydraulic transients; small wave like disturbances in the water surface immediately upstream of the gate, and larger waves which travel the length of the channel reach. These transients can be reduced or eliminated by slower gate movements, which can best be achieved by P Control. It is not recommended that slow gate movement be controlled by the speed of the gate because this restricts it to P Control alone. Rapid gate movement may be desirable in some instances because the water level responds faster and steady state conditions are reached sooner.

The small wave disturbances are very localized, and do not pose a major concern for gate automation. It should be relatively easy to avoid their influence on the control algorithm by using a hydraulic filter. On the other hand, the larger transient waves cannot be easily filtered, and they influence the stability of gate control. The cycling observed in the laboratory associated with this larger transient condition is the same as that observed by others (Gray and Humes, 1972; DeVries and Amorocho, 1973). In both the laboratory and these previous situations, time delayed action reduced or eliminated the transient conditions, thus ensuring control stability.

Optimum times of delay depend on the time it takes for a velocity wave, caused by either gate movement or flow change, to travel up the channel reach. This time, which is defined as celerity, will be a function of channel storage and discharge. In the laboratory this celerity was in the order of 30 to 45 seconds. In the case of the California Aqueduct, this time was 20 minutes (DeVries and Amorocho, 1973).

The waiting time period between execution of gate adjustments (if any) is an important parameter of the control process. Too short a period will increase the frequency of gate adjustments, which will cause unnecessary wave disturbances and promote excessive cycling about the set point. Too long a period will delay the gate response. In situations when the flow rate changes, long times will cause the water level to deviate further from the set point and become more prolonged, until the control action corrects the error. Channel storage and wave celerity will directly influence the optimum value of TW derived for a particular control station.

Response characteristics are mildly sensitive to the flow rate (% of channel capacity). The above relationships for control parameters were developed using a flow rate of about 40% capacity. When the flow rate is considerably reduced below channel capacity, wave disturbances become more pronounced, more gate adjustments are made and cycling increases. These affects can be reduced by modifying the control parameters to increase the response time.

When the flow rate is dramatically increased, and approaches the full conveyance capacity, water level response is much quicker. The affects associated with this are opposite to those with a decrease in flow rate. This allows the control parameters to be modified to provide a quicker response time.

The deadband is a control parameter that affects the accuracy to which the water level achieves the set point. It will primarily be governed by the tolerance between water level and set point, but a minimum value will be desirable to avoid unnecessary gate adjustments close to the set point. Most of the case studies conducted were done using a value of 2.5 mm, which represents about 0.1 % of the maximum desirable operating depth. Values of DB less than this caused frequent minor gate adjustments when the water level was close to the set point, without appreciable changes in the water level. Accuracy of even this amount is not usually demanded in a typical irrigation project. Based on the author's experience, an accuracy of ± 2 % is considered acceptable in most situations.

CHAPTER 10.0

FUTURE RESEARCH

The approach used in this project could easily be used in the field to test and set-up an automatic controller for a pivoting overshot gate or other similar structure. It forms a baseline procedure for such work, which can be improved adding features such as safety commands, emergency alarms and overrides, multiple structure control and remote operation. It also leaves a number of opportunities for additional research activities.

It is unfortunate that the MiniSAFE would not respond using the control blocks concept. Only by this method can this controller be used to provide multiple control such as operation of more than one gate simultaneously. However, this work can be carried on by the University technical staff who are familiar with the hardware, or conducted as undergraduate work under the support of this staff. It was acknowledged by Control Microsystems that the MiniSAFE is not able to provide two direction operation of a gate motor because of limitations in digital output. This can be overcome by SAFE BASIC commands directly, but unless the hardware can be modified to accommodate this operation, it alone may limit the ability of the controller to perform multiple operations.

If the MiniSAFE is able to be applied using the control blocks, it should not be assumed that the same value of control parameters will apply. The units of measurement or time dimensions programmed into the control blocks may not necessarily be identical to those used in the SAFE BASIC programs developed for this project.

This project was conducted in a laboratory setting under a controlled environment. There are a number of operational situations that affect a typical irrigation delivery system. As a follow up to the laboratory work, a similar exercise could be conducted in the field to test the control system to these situations. It would even be prudent to compare the characteristics of the pivoting overshot gate to an undershot gate.

The work conducted in this project examined the characteristics on the basis of non-submerged weir flow. When this structure is operated purely as a check structure it is often under the influence of tailwater, referred to as a submerged condition. Investigations at the undergraduate level can investigate the control characteristics while the gate is under submerged conditions.

An important and relevant piece of research has been done by Schaalje (1991), who compared a number of automatic controllers, including PID Control, by simulation using computer programming. The work was done on the basis of upstream control for an irrigation canal system, using the Irrigation Conveyance System Simulation (ICSS) computer program. The ICSS program has been calibrated and verified on a number of irrigation conveyance systems in Southern Alberta. Further research can be performed to calibrate the computer model for any of the control methods used so that it can subsequently simulate automated control of complex irrigation conveyance systems which incorporate a number of control structures.

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APPENDIX A

SAFE BASIC PROGRAMS

gateold1.bas

```
10 PRINT
20 PRINT
30 PRINT"MiniSAFE OPERATION OF TILTING GATE"
40 PRINT"R.D.CARNDUFF, JULY 22/91"
50 PRINT
60 PRINT
70 INPUT"WATER LEVEL DESIRED (INCHES)";WL
80 IF WL>12 THEN 90:ELSE GOTO 110
90 PRINT"MAXIMUM ALLOWABLE WATER LEVEL = 12 INCHES"
100 GOTO 70
110 INPUT"DEADBAND WATER DEPTH (INCHES)";DB
120 INPUT"WAITING TIME BETWEEN GATE OPERATION (SEC.)";R
130 DEF DOUT 4,6
140 PRINT
150 PRINT
160 PRINT"     Y      "
170 PRINT"------------"
180 Y=AIN(1)/204.6
190 C=2.5
200 O1=((AIN(2)-702)/2.68)/57.2958
210 P=11.344
220 E=Y-WL
230 W1=P*SIN(O1)
240 W2=W1-E
250 L2=(P^2-W2^2)^.5
260 O2=ATN(W2/L2)
270 DO=ABS(O1-O2)*57.2958
280 DT=DO/C
290 PRINT Y
300 MAX=WL+DB
310 MIN=WL-DB
320 IF Y<MAX AND Y>MIN THEN 460
330 IF Y>(MAX)THEN 350
340 IF Y<(MIN)THEN 380
350 TURNOFF 4,1
360 TURNON 4,2
370 GOTO 400
380 TURNON 4,1
390 TURNON 4,2
400 T=0:X=DT*10
410 INTERVAL T,1
420 SETTIMER T,X
430 X=TIMER(T)
440 IF X<>0 THEN 430
450 TURNOFF 4,2
460 T=0:X=R*10
470 INTERVAL T,1
480 SETTIMER T,X
490 X=TIMER(T)
500 IF X<>0 THEN 490
510 GOTO 180
```

gatepid2.bas

```
10 PRINT
20 PRINT
30 PRINT"**************************************
40 PRINT"* MiniSAFE OPERATION OF TILTING GATE *
50 PRINT"*   using P, PI, PD or PID CONTROL   *
60 PRINT"*    R.D.CARNDUFF, NOVEMBER 19/91    *
70 PRINT"**************************************
80 PRINT
90 PRINT
100 INPUT"TARGET WATER LEVEL (INCHES)";WL
110 IF WL>12 THEN 120:ELSE GOTO 130
120 PRINT"MAXIMUM ALLOWABLE WATER LEVEL = 12 INCHES":GOTO 100
130 INPUT"DEADBAND (INCHES)";DB
140 INPUT"WAITING TIME PERIOD (SEC.)";TW
150 INPUT"INCREMENTAL TIME BETWEEN DATA OUTPUT (SEC.)";I
160 INPUT"PROPORTIONAL GAIN ";K
170 INPUT"INTEGRAL RESET TIME (SEC.)";RE
180 INPUT"DIFFERENTIAL RATE GAIN ";RA
190 '
200 ' Level Indicator #1 = Analog Channel 1
210 ' Level Indicator #2 = Analog Channel 2
220 ' Tilt Sensor = Analog Channel 3
230 ' Flow Meter = Analog Channel 4
240 ' Turning on digital channel 4,1 raises gate
250 ' Turning off digital channel 4,1 lowers gate
260 ' Turning on digital channel 4,2 starts motor
270 ' Turning off digital channel 4,2 stops motor
280 '
290 DEF DOUT 4,6
300 PRINT
310 PRINT
320 PRINT" Time(sec) ";"Y1(in.)   ";"Y2(in.)   ";"Q(l/sec)  ";
     "Gate(deg) "
330 PRINT" --------- ";"--------- ";"--------- ";"--------- ";
     "--------- "
340 T=0:' Set start time = 0
350 P=11.344:CO=2.5:D=57.2958
360 '
370 ' Waiting time between gate adjustment and start of next cycle
380 '
390 DT=0:YO=AIN(1)/204.6:ES=0
400 C=0:' Start counting for reading depths at 1 sec. intervals
410 INTERVAL 0,1:SETTIMER 0,10
420 X=TIMER(0)
430 IF X<>0 THEN 420
440 Y1=AIN(1)/204.6:Y2=AIN(2)/204.6
450 E=Y1-WL:C=C+1
460 ES=ES+E:IF C<>I THEN 410
470 T=T+I:DT=DT+I
480 Q=INT(((AIN(4)-694)*.362)*10+.5)/10:
    O=INT(((AIN(3)-702)/2.68)*10+.5)/10
490 PRINT T,INT(Y1*100+.5)/100,INT(Y2*100+.5)/100,Q,O
```

```
500 IF DT<>TW THEN 400
510 DY=Y1-Y0
520 '
530 ' PID Algorithm
540 '
550 CP=K*E:' Proportional Correction Term
560 IF RE=0 THEN 580
570 CI=K/RE*ES*DT:' Integral Correction Term
580 IF RA=0 THEN 600
590 CD=K*RA*DY/DT:' Derivative Correction Term
600 CT=CP+CI-CD:' Total Correction
610 C=ABS(CT)-DB:IF C<=0 THEN 390:' No adjustment if correction <
    deadband
620 '
630 ' Gate Adjustment Algorithm
640 '
650 O1=O/D
660 W1=P*SIN(O1)
670 W2=W1-CT
680 IF W2>P OR W2<0 THEN 840
690 L2=SQR(P^2-W2^2)
700 O2=ATN(W2/L2)
710 DO=ABS(O1-O2)*D
720 DT=DO/CO
730 '
740 ' Gate Adjustment Sequence
750 '
760 IF Y1>WL THEN TURNOFF 4,1:' Lower Gate
770 IF Y1<WL THEN TURNON 4,1:' Raise Gate
780 TURNON 4,2
790 AJ=DT*10:T=T+INT(DT*10+.5)/10
800 INTERVAL 1,1:SETTIMER 1,AJ
810 X=TIMER(1)
820 IF X<>0 THEN 810
830 TURNOFF 4,2:GOTO 390
840 PRINT
850 PRINT"***** WARNING: GATE DIMENSIONS EXCEEDED! *****"
860 PRINT
870 PRINT"TOTAL CORRECTION IS TOO GREAT. RUN THE PROGRAM AGAIN USING
    ONE"
880 PRINT"OR A COMBINATION OF THE FOLLOWING:"
890 PRINT
900 PRINT"     1. REDUCE PROPORTIONAL GAIN!"
910 PRINT"     2. INCREASE INTEGRAL RESET TIME!"
920 PRINT"     3. INCREASE DIFFERENTIAL RATE GAIN!"
930 END
```

SAMPLE RUN

CASE 141 - PID CONTROL

```
RUN

*************************************
* MiniSAFE OPERATION OF TILTING GATE *
*   using P, PI, PD or PID CONTROL   *
*    R.D.CARNDUFF, NOVEMBER 19/91    *
*************************************

TARGET WATER LEVEL (INCHES)? 7
DEADBAND (INCHES)? .1
WAITING TIME PERIOD (SEC.)? 10
INCREMENTAL TIME BETWEEN DATA OUTPUT (SEC.)? 1
PROPORTIONAL GAIN ? .5
INTEGRAL RESET TIME (SEC.)? 500
DIFFERENTIAL RATE GAIN ? -5
```

Time(sec)	Y1(in.)	Y2(in.)	Q(l/sec)	Gate(deg)
1	5.02	5.09	15.2	13.8
2	5.01	5.09	15.2	13.4
3	5.02	5.09	15.2	13.1
4	5.02	5.08	15.2	13.8
5	5.01	5.08	15.6	13.1
6	5.02	5.09	15.6	13.4
7	5.02	5.09	15.6	13.1
8	5.02	5.09	15.6	13.8
9	5.02	5.09	15.6	13.1
10	5.02	5.09	15.2	13.8
13.5	5.04	5.06	15.2	20.1
14.5	5.22	5.09	15.6	20.1
15.5	5.41	5.06	15.2	20.1
16.5	5.56	5.07	15.2	20.1
17.5	5.66	5.09	14.8	20.1
18.5	5.68	5.09	15.6	20.5
19.5	5.68	5.21	15.6	20.5
20.5	5.66	5.4	15.6	19.8
21.5	5.59	5.46	15.2	20.1
22.5	5.54	5.54	14.8	20.1
25.1	5.35	5.64	14.8	24.6
26.1	5.32	5.73	15.2	24.6
27.1	5.39	5.75	14.1	23.5
28.1	5.51	5.81	15.2	24.6
29.1	5.81	5.84	15.2	24.6

30.1	6.03	5.91	15.2	24.6
31.1	6.1	6.01	15.2	24.6
32.1	6.31	6.04	14.8	24.6
33.1	6.32	6.06	14.1	23.5
34.1	6.32	6.09	15.2	24.6
35.6	6.29	6.18	15.6	25.4
36.6	6.28	6.33	15.6	25.4
37.6	6.18	6.44	15.2	25.4
38.6	6.15	6.46	15.2	25.7
39.6	6.15	6.48	15.2	25.7
40.6	6.26	6.51	14.8	25.4
41.6	6.35	6.5	15.6	25.4
42.6	6.52	6.55	15.2	25.4
43.6	6.59	6.57	15.2	25.7
44.6	6.71	6.61	15.2	25.4
45.9	6.76	6.66	15.2	26.1
46.9	6.76	6.69	15.6	26.1
47.9	6.77	6.73	15.2	26.1
48.9	6.79	6.75	15.2	26.1
49.9	6.77	6.8	15.6	26.1
50.9	6.79	6.81	15.6	26.1
51.9	6.77	6.85	15.6	25.7
52.9	6.79	6.91	15.6	26.1
53.9	6.81	6.93	15.2	25.7
54.9	6.86	6.95	15.6	25.7
55.9	6.92	6.98	15.6	25.7
56.9	6.94	7.01	15.6	25
57.9	6.96	7	15.6	25.7
58.9	7.01	7.05	15.6	26.1
59.9	7.03	7.05	15.6	26.1
60.9	7.03	7.06	15.6	25.7
61.9	7.04	7.08	15.6	25.7
62.9	7.06	7.08	15.6	26.1
63.9	7.06	7.08	15.2	25.7
64.9	7.06	7.1	15.6	25.7
65.9	7.09	7.1	15.2	26.1
66.9	7.08	7.13	15.6	25
67.9	7.08	7.12	15.6	26.1
68.9	7.11	7.2	15.6	25.7
69.9	7.11	7.21	15.6	25
70.9	7.1	7.23	15.6	26.1
71.9	7.16	7.23	15.6	25
72.9	7.16	7.23	15.6	26.1
73.9	7.17	7.23	15.6	26.1
74.9	7.19	7.23	15.6	26.1
76.2	7.2	7.23	15.6	25.4
77.2	7.21	7.26	15.6	25.4
78.2	7.2	7.26	15.2	25.4
79.2	7.18	7.26	15.2	25.4
80.2	7.19	7.26	14.1	25
81.2	7.21	7.26	14.8	25
82.2	7.2	7.26	14.8	25.4

83.2	7.2	7.26	15.2	25.4
84.2	7.19	7.26	15.2	25.4
85.2	7.2	7.26	15.6	25
86.5	7.21	7.26	15.2	25
87.5	7.21	7.26	15.6	24.6
88.5	7.2	7.26	15.6	25
89.5	7.21	7.25	15.2	25
90.5	7.2	7.26	15.2	25
91.5	7.2	7.26	15.6	25
92.5	7.2	7.26	15.2	25.4
93.5	7.18	7.25	15.2	25
94.5	7.19	7.25	15.2	25
95.5	7.19	7.25	15.2	25
96.8	7.19	7.25	15.6	25
97.8	7.18	7.25	15.2	24.3
98.8	7.19	7.25	14.8	24.6
99.8	7.18	7.25	15.2	23.5
100.8	7.19	7.25	15.6	24.6
101.8	7.18	7.25	14.8	24.6
102.8	7.19	7.25	15.6	24.6
103.8	7.16	7.25	14.8	24.6
104.8	7.15	7.23	14.1	24.6
105.8	7.16	7.23	15.6	24.6
106.8	7.16	7.22	15.2	24.3
107.8	7.15	7.23	14.8	24.6
108.8	7.16	7.21	14.8	24.6
109.8	7.15	7.2	15.2	24.6
110.8	7.16	7.21	15.6	23.5
111.8	7.15	7.21	15.6	24.6
112.8	7.15	7.2	14.1	23.5
113.8	7.16	7.2	15.2	24.3
114.8	7.1	7.2	15.2	23.5
115.8	7.11	7.2	14.1	24.3
116.8	7.11	7.2	14.1	23.5
117.8	7.11	7.2	14.8	24.6
118.8	7.11	7.21	14.1	24.6
119.8	7.11	7.13	15.2	24.3
120.8	7.11	7.13	14.8	24.6
121.8	7.11	7.13	15.2	24.6
122.8	7.1	7.13	15.2	23.5
123.8	7.09	7.11	14.1	24.6
124.8	7.08	7.13	15.2	23.5
125.8	7.08	7.13	15.2	24.6
126.8	7.08	7.12	15.2	24.6
127.8	7.08	7.13	15.6	23.5
128.8	7.09	7.13	15.2	24.6
129.8	7.08	7.13	15.2	24.6
130.8	7.09	7.13	15.6	24.6
131.8	7.07	7.13	15.6	24.6
132.8	7.09	7.1	14.8	24.6
133.8	7.07	7.1	15.2	24.6
134.8	7.09	7.1	15.2	24.6

135.8	7.09	7.1	15.2	24.6
136.8	7.07	7.1	15.6	24.6
137.8	7.09	7.1	14.8	24.6
138.8	7.06	7.1	15.2	24.6
139.8	7.06	7.1	15.2	24.6
140.8	7.06	7.1	15.2	24.6
141.8	7.08	7.1	15.2	23.5

HALT IN LINE 430
OK

APPENDIX B

MISCELLANEOUS LABORATORY APPARATUS DATA

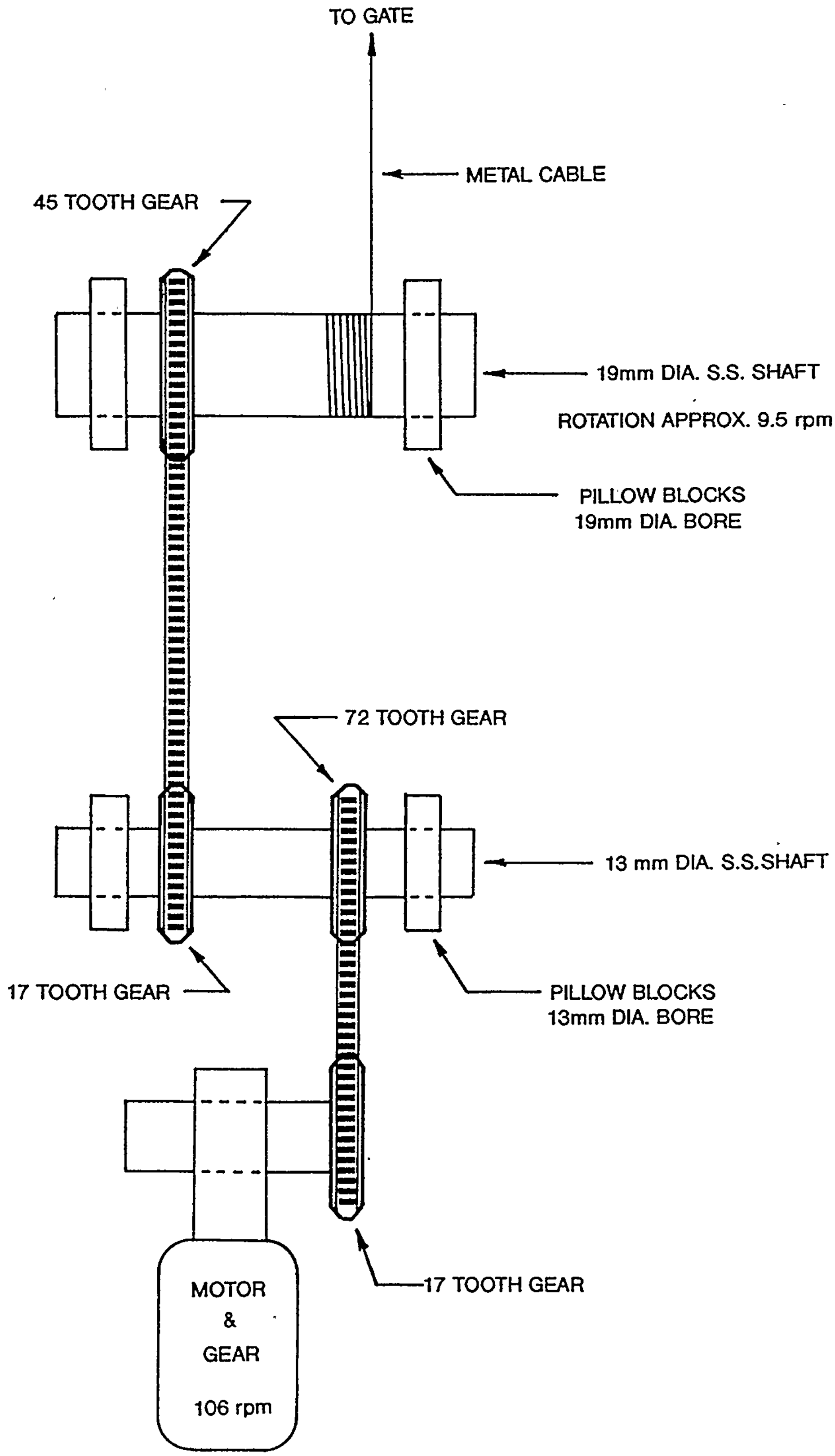
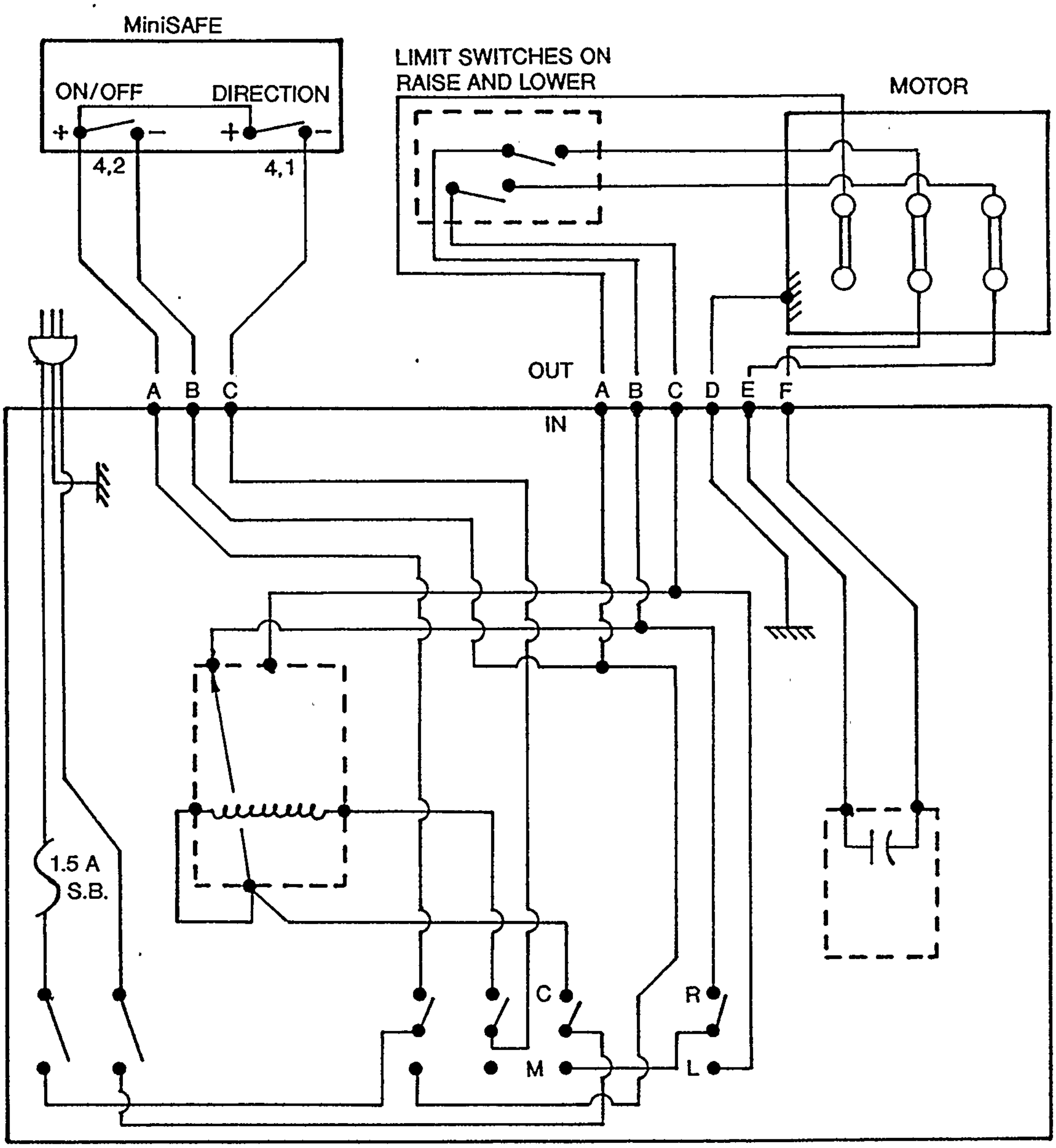


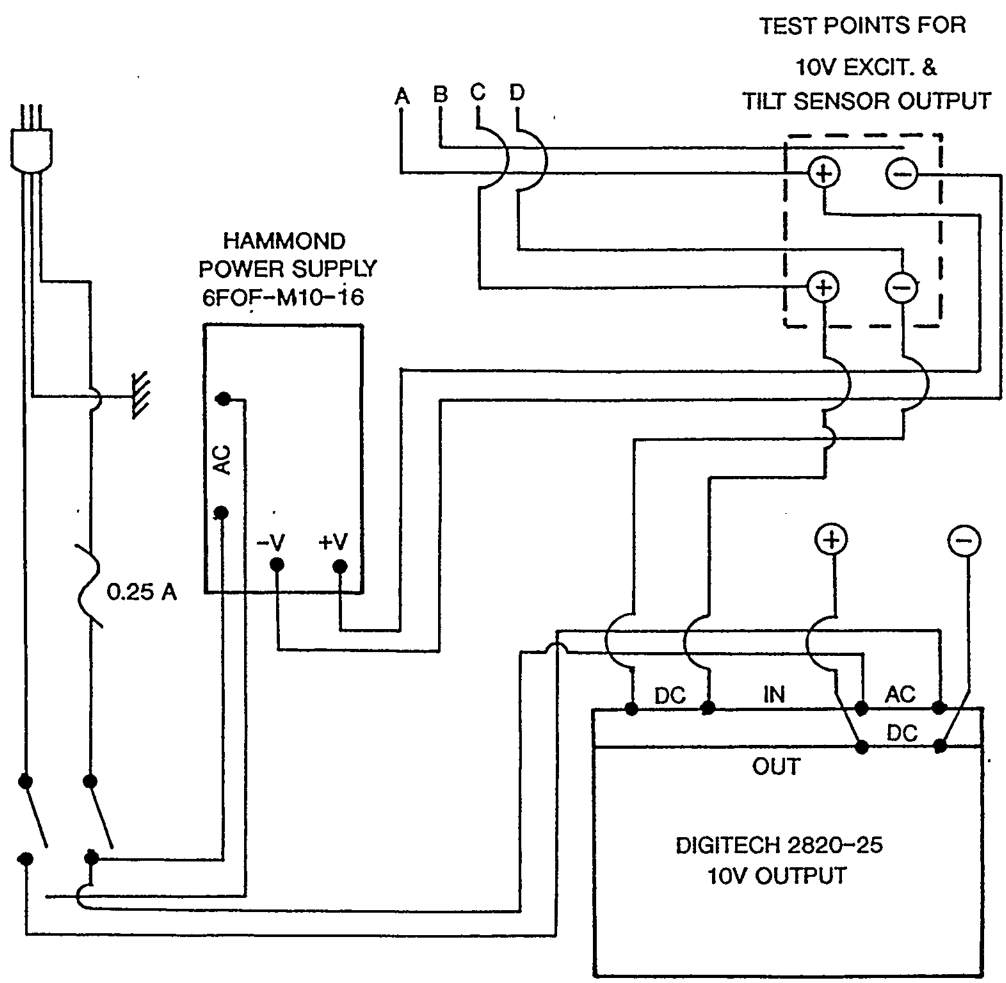
Figure B1 - Schematic of Electric Gate Winch



MOTOR CONNECTORS:

Pin	In	Out	Description	
A	White	White	Power To Motor	4 Conductor Cable
B	Black	Black	Motor Forward (Gate Up)	
C	Red	Red	Motor Reverse (Gate Down)	
D	Green	Green	Ground	
E	White	Grey		2 Conductor Cable
F	Black	Grey		

Figure B2 - Wiring Schematic For Motor Control (Winch)



Connector		Tilt Sensor		
A - White	10V+	In -	Red	10V+
B - Black	10V-		Black	10V-
C - Blue*	Tilt Sensor +	Out -	Green	+
D - Grey*	Tilt Sensor -		White	-

* Output From Tilt Sensor

Figure B3 - Wiring Schematic For Tilt Sensor