EMERGENCY GATE CLOSURES

SUMMARY MEMORANDUM REPORT 1985-1987

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INTRODUCTION

A review of Bureau of Reclamation projects found that a significant number of outlet works structures have inadequate air venting to allow for safe closure of the emergency gate under unbalanced head conditions. In an effort to upgrade these facilities and develop a standardized test procedure for the Safety of Dams program, several investigations were conducted by the Hydraulics Branch. These investigations included: a 1:12 scale hydraulic model of Cedar Bluff Dam outlet works, laboratory tests of a 4-inch air vacuum-release valve, field studies on the Silver Jack Dam outlet works, and development of a mathematical model to be used in evaluation and sizing of automatic air valves.

SUMMARY

Model and prototype studies showed that venting the conduit between the emergency gate and the control gate with an automatic air valve was an effective method for reducing the magnitudes of negative pressures generated by closing the emergency gate under unbalanced head conditions. In most cases, the pressures can be increased enough to prevent collapse of the pipeline; however,some sites may need additional stiffeners as well as the automatic air valve in order to prevent damage.

The prototype 4 inch air vacuum-release valve performed up to the manufacturers claims. Slightly more air flow was measured at the same pressure differentials than reported in the manufacturers literature. Operation and maintenance of the valve poses no problem. A relatively simple design and few moving parts results in a dependable and durable unit.

While maintenance on the air valve itself is minimal, proper care must be taken that the air passages leading from the valve to the conduit are clear and free of obstructions. Field investigations showed that air manifolds in the downstream frame of the emergency gate are particularly vulnerable to fouling. If these passages (usually 1 to 1.125 inch diameter holes) become restricted, the air valve is rendered useless and the outlet works conduit may be in danger if the emergency gate is closed under unbalanced head.

A standardized emergency gate test procedure was proposed and tested. This procedure allows for testing at the maximum loading of the gate hoist while requiring only minimal air demand.

The computer model showed good agreement with the data collected in the model tests of Cedar Bluff and the prototype tests at Silver Jack. Some adjustments still need to be made, including improvement of the presentation of the data output, i.e. tables and graphs.

INVESTIGATIONS

I. Model Study: Cedar Bluff Dam Outlet Works

Cedar Bluff Dam, completed in 1951, is located in north central Kansas. It features a single conduit, gated outlet works structure which delivers water for irrigation and other downstream requirements. Typical of many other Bureau outlet works, the emergency gate is located in a chamber, several hundred feet upstream from the control gate, figure 1. Normally the emergency gate operates as a guard gate under balanced head conditions. On occasion, it may be necessary to close the emergency gate while the control gate is partially or fully open. If this situation arises, air must be supplied to the conduit between the emergency gate and the control gate, to prevent damage or collapse of the pipe due to low pressures. This study was designed to observe the structure operating with unbalanced heads across the emergency gate, with special attention paid to the air demand and pressures downstream from the emergency gate.

a) The Model

A 1:12 scale Froudian model of the Cedar Bluff Dam outlet works was constructed in the hydraulics laboratory. The main feature of the model was a variable speed, motor operated emergency gate, figure 2. Water was supplied to the model through the laboratory system. A free surface constant head tank with an overflow weir, provided a continuous head equivalent to the maximum design water surface. An 8 inch diameter pipe lead to the emergency gate structure where several piezometers were located for pressure measurements. A scaled air vent was included downstream from the emergency gate. Air flows were measured at this point, figure 3. The conduit between the emergency gate and the control gate was simulated with 5.5-inch diameter clear acrylic plastic pipe to facilitate flow observations. The control gate was an adjustable slide gate.

A microcomputer based data acquisition system was used to read data from the instrumentation and to record, analyze, and plot results. Quantities which were measured included:

(1) emergency gate discharge measured with a strap-on acoustic flowmeter

(2) emergency gate position, using a string transducer

(3) pressures on the gate leaf and surrounding chamber surfaces, using a differential pressure transducer and scanivalve

(4) air demand downstream of the emergency gate, using an orifice plate and differential pressure transducers and

(5) dynamic pressure fluctuations in the conduit between the emergency gate and the control gate, using piezoelectric pressure transducers.

b) The Study

Model tests were conducted at two emergency gate closure rates, and five downstream control gate positions. The model gate closure rates were scaled to simulate prototype rates of 1 ft/min and 2 ft/min. For each closure rate, control gate positions of 20, 40, 60, 80, and 100 percent were tested. The test procedure consisted of setting a control gate position, establishing steady state flow conditions, and then initiating closure of the emergency gate. As the emergency gate was closing the computer polled the instrumentation, reading all quantities of interest as a function of the emergency gate position at any point in time.

c) Results

The model results revealed several interesting points. Air demand for the various unbalanced head conditions tested as a function of gate position is shown in figure 4. These curves are for the 1 ft/min closure rate. The demand was very steady except when the vent just opened, and when the hydraulic jump exited the conduit. At the 1 ft/min rate, the hydraulic jump exited the conduit prior to full closure of the emergency gate closure for all control gate settings tested. However, at a 2 ft/min closure rate, the emergency gate closed before the jump exited the conduit. The air demand curves were modified due to this influence, figure 5. The point where the air demand begins shifts down slightly on the y-axis and the curve intercepts the axis (0 percent gate opening) with a small residual air flow. When the gate closed before the jump exited the conduit a wave travelled up the conduit, hitting the downstream face of the emergency gate leaf. The closure rate at most field sites will be, at maximum, 1 ft/min, and probably slower depending on reservoir head, temperature, and the amount of unbalanced head the gate is closing under. Therefore, the length of the conduit between the emergency gate and the control gate will be the primary factor in determining whether the hydraulic jump exits the conduit prior to full closure.

Pressures measured on the gate showed that the bottom of the gate leaf remained under vapor pressure during the entire length of gate travel, figure 6. The wide seats on this style of gate leaf have been subject to cavitation damage and high downpull forces in the past.

d) Discussion

The main topic of interest, air demand, is one of the more difficult quantities to simulate in scale models due to scale effects inherent in modeling air-water flows. Scale effects in these types of flows are generally due to the inability to reproduce the fine scale turbulence levels present in prototype flow. The air demand in this case however, is driven by the pressure in the conduit and the moving hydraulic jump, both mechanisms are large scale. Scaling therefore is not a significant problem as long as the losses in the air valve and vent system are modeled correctly. Pressures on the gate leaf and in the surrounding gate frame should scale satisfactorily, with the exception of vapor pressure in the prototype structure, which will not correctly scale in the model since the fluid properties (density and viscosity) are not scaled down, i.e. water is used as the working fluid in the model and the prototype. The pressures on the gate leaf indicate an unusual change in control with changes in gate position. The influence of the curved floor in the gate frame is also apparent from the data. A short tube effect is created at small openings.

The dynamic pressure fluctuations measured in the model were as expected. The fluctuations were highest when the hydraulic jump was passing over a transducer, the levels otherwise were insignificant. Scaling the dynamic pressure amplitude and frequency for the case of a hydraulic jump has been proven successful by a number of researchers. The highest magnitude of the fluctuations measured in the model should not pose a problem to the conduit.

II. Laboratory Tests: 4-inch Air Vacuum-Release Valve

A typical 4-inch air combination release valve was tested in the hydraulic laboratory under a variety of conditions. In most applications, these air valves are designed for evacuating accumulated air from the pipeline. However, during an emergency gate closure, the main interest are the inflow characteristics. Of specific interest is the coefficient of discharge for the valve, to allow for proper sizing to alleviate low pressures in the conduit.

a) Test Setup

There were two configurations used to test flow through the air valve. The valve was first mounted inside an air plenum and air was blown through it using a large centrifugal fan, figure 7. Flow to the valve was measured with an in-line orifice meter. The pressure difference across the valve was measured with two pressure transducers; one sensing the plenum pressure and another mounted on a piezometer ring on the valve discharge line. Temperature and barometric pressure were also recorded. Due to limitations in the air flowrates with this setup, an additional group of tests were run. These tests consisted of mounting the air valve on a large vacuum chamber (Low Ambient Pressure Chamber) located in the hydraulic laboratory. In this configuration, the air valve was mounted on a standpipe outside of the chamber. An in-line orifice meter measured the discharge. The valve was isolated from the chamber by a quick closing butterfly valve. The butterfly valve was closed while a subatomospheric pressure was drawn in the chamber. When the desired negative pressure was reached, the butterfly valve was opened, allowing air to flow into the chamber through the air valve.

Operation and maintenance characteristics of the air valve were evaluated using a test stand in the lab, figure 8. A series of cycling tests were performed by opening and closing a motor-operated butterfly valve. Water was supplied with a portable pump while the level in the standpipe leading up to the air valve oscillated due to the opening and closing of the butterfly valve. Pressure transducers were located on the standpipe and the air valve body. Minimum seating pressures and the frequency of unsuccessful seating attempts were measured. Disassembly of the air valve for inspection of the internal parts was performed after this series of tests.

b) Results

The air inflow characteristics of the air vacuum-release valve are shown in figure 9. The first test arrangement did not allow adequate air capacity to determine a meaningful discharge coefficient for comparison with the manufacturer's data. The LAPC tests however, revealed an average discharge coefficient of 0.4, figure 10. The manufacturers curves for a similar valve indicate a value of 0.44 for C_d. The discharge coefficient measured in the laboratory was based on the pressure differential measured at the lower drain tap. Since this tap is near the bottom flange, losses in the valve between this tap and the flange can be assumed to be negligible.

The minimum internal seating pressure, to prevent leakage was 3 lb/in^2. This pressure could then be reduced to 1.5 lb/in^2 without losing the seal. The valve was cycled 580 times without any operational failures. A thorough inspection of the valve after these tests did not detect wear on the seat or float. The inner metallic surfaces had a light coating of rust, figure 11. All the moving parts were in good condition.

c) Discussion

Automatic air valves were tested from two different manufacturers. The operation of the valves was found to conform to the manufacturers' published data, as far as air flow capacities. The cycling of the valve did not reveal problems in seating although leakage could occur if internal valve pressures remain below 3 lb/in^2. Maintenance of the valves should be simple, since movable parts are minimal and easily accessible.

III. Prototype Tests: Silver Jack Dam Outlet Works

In October 1986 and May 1987, field tests were performed on the outlet works at Silver Jack Dam. The dam, completed in 1971, is located on the Cimarron River near Montrose, Colorado. It features a single conduit outlet works with a 2.75 ft by 2.75 ft emergency gate feeding a 38-inch diameter conduit which bifurcates near the exit and terminates with two 2.25 ft by 2.25 ft control gates in each outlet, figure 12. The emergency gate is a typical 45-degree gate leaf with no upstream skin plate, figure 13. The emergency gate was equipped with an automatic 4-inch air vacuum-release valve. Silver Jack was selected for testing since it has a conduit which is small enough (38 inch diameter) to withstand vapor pressure without endangering the pipe yet large enough to enter the pipe to install instruments. The site also met other requirements such as type of control gate, downstream channel capacity and water availability.

a) The Tests

The testing was done during two separate trips, one in October 1986 and the second in May 1987. The testing included measurement of the downpull and uplift forces on the emergency gate under balanced and unbalanced head conditions. A sample of the proposed standard emergency gate test procedure proposed for the Safety of Dams program was run. In addition, air demand through the 4-inch air valve was measured for three unbalanced head conditions. During these tests, conduit pressures (both static and dynamic) were monitored along with accelerations on the steel conduit between the emergency gate and the control gates.

b) Results

The test results will be summarized for each of the trips. The first tests were performed October 6-10, 1986. A set of measurements were made on the gate for balanced head conditions, figure 14. The net force required for gate operation was determined by monitoring pressures in the hydraulic cylinder of the emergency gate. A positive net force is in the downward direction. The data for both directions of gate movement show a symmetrical pattern centered around the submerged weight of the gate (1400 lb). The sloping linear behavior in the force curve is due to friction from the gate moving out of and into the gate frame. In the frame section the gate slots surround the leaf however, as the gate rises into the bonnet section, only a downstream seat exists, and the net force decreases due to the reduced friction. The slight bulge in each curve at the 25-percent opening is probably due to a slight misalignment in the joint between the gate frame and bonnet cover.

The proposed standard emergency gate test was also performed. The emergency gate was opened to approximately 20-percent and then closed again under totally unbalanced head (with the downstream conduit initially dewatered.) This test procedure will allow the hoist cylinder to be operated under maximum loading conditions (as determined by testing through a full range of operations at Silver Jack) without requiring operation of the automatic air valve, since the air demand can be satisfied by the fully open control gate at the end of the conduit. Results of this test are shown in figure 15. The force required to begin movement of the gate corresponds to static loading and a starting friction coefficient of 0.6. The additional increase in downpull between 0 and 5 percent (the bulge in the opening portion) is due to vapor pressure acting on the bottom seat of the gate leaf. As the gate rises past the 15 percent opening, the upper seat on the gate leaf moves off the upper seat on the downstream frame, a slight misalignment at this point may be responsible for the increase in the upward force required. The closing portion shows that a steadily increasing force is needed to overcome the friction and close the gate.

A series of three tests were run under unbalanced head conditions. The control gates on each of the outlet pipes were set at symmetric opening of 25 percent, 50 percent, and 75 percent; which corresponded to 33.5 percent, 66.9 percent and 100.4 percent openings referenced to the emergency gate area. In each case, the emergency gate was fully open initially, and a steady state flow was established, then the emergency gate was closed. Three sets of results are presented: 1) forces on the emergency gate leaf, 2) static pressures in the 38-inch conduit, and 3) air demand at the 4-inch air valve. Gate hoist loading, figure 16, can be explained by looking at the gate leaf area exposed to the flow at specific gate openings. At 85 percent open, the gate leaf is subjected only to upthrust on the bottom sloping section of the gate leaf, whereas at the 60 percent opening, upthrust and downpull are nearly balanced due to the upper sloping surface entering the flow, figure 17. Below the 60 percent opening, frictional forces become dominate and increase as the gate closes.

In all cases of the unbalanced head conditions, the emergency gate closed at a rate of 0.67 ft/min. Data for the 25 percent control gate settings are shown in figure 18 a and b. The conduit pressures at four different stations show the decrease in pressure from the reservoir head to a negative pressure at gate openings below 10 percent. The pressure does not recover, meaning that the hydraulic jump has not exited the conduit before the emergency gate is fully closed. The air demand data shows the air valve opening and drawing air at about a 21 percent emergency gate opening. The air demand however is rather erratic, fluctuating wildly, and not reaching expected levels. The air demand continues for some time after the emergency gate has closed, reinforcing the idea that the hydraulic jump is still in the conduit at the time of closure. The data for 50 percent control gate openings is shown in figure 19 a and b. The conduit pressures again decrease with the closing of the emergency gate. The stations further downstream, STA 6+19 and STA 7+39, have lower pressures at larger gate openings due to frictional losses in the conduit. The crown pressure at STA 4+35 nearly reaches full vapor pressure at a 20 percent gate opening, and doesn't fully recover before the gate is closed. Again, the hydraulic jump is still in the conduit or is just exiting at the moment of closure. The air demand begins at an emergency gate position of 44 percent. The demand again is very sporadic and much lower than anticipated. The data for 75 percent control gate openings (equivalent to 100.4 percent of the emergency gate area or fully unbalanced) is shown in figure 20 a and b. The conduit pressures are similar to those seen in the previous test, with the conduit exposed to vapor pressure at a 40 percent emergency gate opening. The pressure however does recover, indicating that the hydraulic jump has exited the conduit before the gate is fully closed. The air demand begins at an emergency gate position of 62 percent. As with the previous tests, the demand fluctuates wildly and is much lower than anticipated.

The second series of tests occurred May 26-29, 1987. These tests resulted from the need to get a better understanding of the air demand data which was acquired during the first test series. The predictions of air demand for Silver Jack were much higher than the measured data. At first it was suspected that there was a problem with the transducer measuring the pressure differential across the air valve. The second test series included air demand measurements along with emergency gate position and several conduit pressures and accelerations. In addition, audio and video recordings were made in the unattended gate chamber to assist in determining what was occurring throughout the tests. As a result of a higher reservoir head and colder temperatures, the emergency gate closure rate was about twice as slow as in the previous test. The tests began with an emergency gate closure at 25 percent control gate settings, figure 21 a and b. Again there were low air flow rates and high negative pressures. The 50 percent control gates test was run, figure 22 a and b, and continued to show low air flow rates and high negative pressures. The instruments were checked and were functioning properly. It was then decided to video the next test to try and observe operation of the valve. A streamer was tied near the air intake of the valve so that at least qualitative strength and direction of air movement could be determined. A test at 75 percent control gate openings was run, figure 23 a and b. The instrumentation again indicated much lower than expected air flows with full vapor pressure in the conduit. The video tape was reviewed and showed only a very weak air flow into the automatic air valve. A strong blow back (out of the conduit) was noticed near the end of the gate closure. This blow back occurred as the hydraulic jump exited the downstream end of the conduit, allowing air to rush in, relieving the lower pressures inside the pipe. The weak airflow in conjunction with a pressure differential of nearly 11 lb/in^2 could only be caused by a blockage of the air flow path. The gate was closed and the downstream gate frame and air piping were inspected. By looking up through the air manifold from inside the conduit, it was evident that a layer of silt had deposited on top of the downstream gate frame, figure 24. Fourteen 1-inch diameter holes were counted in the crown of the downstream gate frame. The average open diameter of the holes was estimated to be 0.5 inches. The silt reduced the flow area from 11 in^2 to about 2.7 in^2. As much of the silt was cleared from the holes as was possible before resuming testing. It was also noted that Specification No. 860-D-85 requires sixteen 1.125-inch diameter holes in the downstream gate frame for air venting purposes (as opposed to the fourteen 1 inch diameter holes observed.)

With the air vent configuration now closer to the design, a closure test with 50 percent control gate openings was repeated. Data showed that there was a large increase in air demand and that the maximum negative pressures in the conduit were reduced from -11 lb/in^2 to -6 lb/in^2, figure 25 a and b. Finally a test with 75 percent control gate openings (fully unbalanced) was run with similar results, figure 26 a and b. Compare figures 23 and 26 for conditions with and without clogged holes in the air vent manifold.

c) Discussion

The field investigations were extremely valuable in evaluating the closure of an emergency gate under unbalanced head conditions. Of particular interest was the much slower closure rate and the plugging of the air manifold with silt in the downstream gate frame. The slow closure rate is actually a benefit since it reduces the transient pressures to a minimum and allows the hydraulic jump to completely exit the conduit before the gate closes and allows air to enter the conduit from the downstream end under most unbalanced head conditions. The item of plugged air passages is much more serious and needs attention in all similar Bureau structures. With a properly sized automatic air valve, collapse of the downstream conduit is still a possibility if any of the air passages are plugged with debris. This debris can be deposited through normal operation as noted by the silt deposits found at Silver Jack Dam. Thorough and frequent inspections of the air passages should be made to insure the integrity of the structure. The size of the holes transmitting air into the conduit should be large enough to avoid plugging with deposits.

IV. Mathematical Model

A computerized mathematical model has been developed to evaluate the large number of outlet works which need to have either air vents sized or to determine if reinforcement of the conduit is required. In the past, site specific models and a generalized steady state math model have been used to size air valves and make further recommendations.

a) The Mathematical Model

The model is based on a computational technique known as the Method of Characteristics[1]. This method used generally for transient analysis, is well suited to this type of problem. Computationally it is simple to program and understand. The only real difficulty in applying this method is in the development of special boundary conditions. The characteristics method is based on simplified equations of motion and continuity, (symbols are defined in Appendix 1),

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[1] Fluid Transients, E.B. Wylie, V.L. Streeter, McGraw-Hill Inc., New York, NY, 1978.

$$0 = g(\partial H/\partial x) + \partial V/\partial t + f/2D(V|V|) \quad (1)$$

$$0 = \partial H/\partial t + a^2/g(\partial V/\partial x) \quad (2)$$

Through a linear combination of these two equations, they can be converted from two partial differential equations to two total differential equations,

$$g/a(dH/dt) + dV/dt + f(V|V|)/2D = 0 \quad (3)$$

$$-g/a(dH/dt) + dV/dt + f(V|V|)/2D = 0 \quad (4)$$

where equation 3 is valid when $dx/dt = +a$, and equation 4 is valid when $dx/dt = -a$. The grouping of each of these equations with its validating conditions gives the commonly referred to C^+ and C^- equations. Visualizing the solution in the *xt* plane, solutions of the equations $dx/dt = \pm a$, gives two straight lines (assuming a is constant) or characteristic lines, along which equations 3 and 4 are valid, figure 27. The development of these equations into a model is done by integrating equations 3 and 4 along the C^+ and C^- lines. The pipe is divided into N reaches, each Δx in length with a time step given by $\Delta t = \Delta x/a$. This basic finite difference formulation yields two equations for the pressure head at point P,

$$C^+ : \quad H_p = H_A - a/gA(Q_P - Q_A) - (f\Delta x/2gDA^2)Q_A|Q_A| \quad (5)$$

$$C^- : \quad H_p = H_B + a/gA(Q_P - Q_B) + (f\Delta x/2gDA^2)Q_B|Q_B| \quad (6)$$

The solution then requires that H and Q be computed for each grid point for the time duration desired. At the interior grid points, the two equations can be solved simultaneously for the unknowns Q_{Pi} and H_{Pi}. Equations 5 and 6 can then be written as,

$$C^+ : H_{Pi} = C_P - a/gA(Q_{Pi}) \quad (7)$$

$$C^- : H_{Pi} = C_M + a/gA(Q_{Pi}) \quad (8)$$

where $C_P = H_{i-1} + a/gA(Q_{i-1}) - (f\Delta x/2gDA^2)Q_{i-1}|Q_{i-1}|$ and $C_M = H_{i+1} - a/gA(Q_{i+1}) + (f\Delta x/2gDA^2)Q_{i+1}|Q_{i+1}|$. Elimination of Q_{Pi} from equations 7 and 8 gives a direct solution for H_{Pi},

$$H_{Pi} = (C_P + C_M)/2. \quad (9)$$

After the first time step, the end (or boundary) points begin influencing the interior points, so for a complete and accurate solution at any time step, the appropriate boundary conditions must be applied.

b) Boundary Conditions

Specification of appropriate boundary conditions allows the problem to be solved for conditions which simulate the real world. Most boundary conditions are fairly straight forward with the main exception being the automatic air valve. Details of the boundary conditions used in this model are given below.

End Conditions

The ends of the pipeline can yield only one valid characteristic equation. Therefore, an auxiliary condition that specifies Q_P, H_P, or some relation between them must be given.

1) Reservoir at upstream end with specified elevation

This case gives $H_{P1} = H_{Res}$, so that Q_{P1} can be determined by a direct solution of equation 10,

$$Q_{P1} = (H_{P1} - C_M) / (a/gA) \tag{10}$$

here the subscript 1 refers to the upstream or reservoir section with the other unknowns being dependant only on known values from the previous time step.

2) Gate at the downstream end

A gate at the downstream end of the system can be handled with the orifice equation for flow through the gate,

$$Q_P = C_d A_g [2g\Delta H]^{½}, \tag{11}$$

where C_d is the discharge coefficient, A_g is the area of the gate and ΔH is the instantaneous drop in hydraulic grade line across the gate. In terms of the model parameters,

$$Q_{Pe} = -a/gA((Q_o\tau)^2/2H_o) + [((a/gA)(Q_o\tau)^2/2H_o)^2 + 2(Q_o\tau)^2/2H_o(C_P)]^{½}, \tag{12}$$

$$H_{Pe} = C_P - a/gA(Q_{Pe}), \tag{13}$$

where τ is the dimensionless gate opening given by,

$$\tau = C_d A_g / (C_d A_g)_o, \tag{14}$$

with $\tau=1$ for steady state flow and $\tau=0$ for a closed gate. The coefficients of discharge for two different gate leafs will be provided in the program.

Change in pipe diameter

A change in the pipeline diameter can be handled by matching conditions at an intersecting node. This same method can be used to simulate a simple series connection. Continuity of discharge and pressure head are enforced at the connecting point,

$$Q_{1,e} = Q_{2,1} \quad (15)$$

$$H_{1,e} = H_{2,1}. \quad (16)$$

Solving these equations simultaneously along with equations 7 and 8 gives,

$$Q_{p2,1} = (C_{P1} - C_{M2})/((a/gA)_1 + (a/gA)_2) \quad (17)$$

The rest of the unknowns can then be determined directly.

Emergency gate in-line

The boundary condition for the closing emergency gate is handled similarly to the control gate at the pipeline end. Basically here, continuity is applied at the gate forcing,

$$Q_{p2,1} = Q_{p1,e} = Q_o\tau/(H_o)^{½}[H_{p1,e} - H_{p2,1}]. \quad (18)$$

With flow in the positive direction, this equation can be combined with equations 7 and 8 to yield a quadratic equation and solved for,

$$Q_{p1,e} = -C_v(B_1 + B_2) + [C_v^2(B_1 + B_2)^2 + 2C_v(C_{P1} - C_{M2})]^{½}, \quad (19)$$

where $C_v = Q_o^2\tau^2/2H_o$ and B_1 and B_2 refer to (a/gA) for the sections upstream and downstream of the gate. If flow happens to reverse directions, all the signs in the above equation are simply reversed as well. Once the flow is known, equations 7 and 8 can be used to find the hydraulic grade line.

Automatic Air Valve

This condition allows for the inflow of air when the line pressure at an air valve drops below atmospheric. When the pressure in the conduit increases above atmospheric, trapped air is allowed to escape at a much slower rate; however, water is not permitted to escape. When the pressure head drops below the conduit elevation, the air valve opens, and air enters according to the ideal gas law,

$$pV = mRT \quad (20)$$

This equation must be satisfied at the end of each time increment as long as the pressure stays reduced. In terms of the model parameters, equation 20 becomes,

$$p[V_i + ½\Delta t(Q_i - Q_{PXi} - Q_{PPi} + Q_{Pi})] = [m_o + ½\Delta t(\dot{m}_o + \dot{m})]RT \quad (21)$$

The characteristic equations are,

$$C^+: \quad H_{Pi} = C_P - B(Q_{PPi}) \tag{22}$$

$$C^-: \quad H_{Pi} = C_M + B(Q_{Pi}) \tag{23}$$

in addition, the relationship between p and H_p is,

$$\gamma(H_p - z + \bar{H}) = p. \tag{24}$$

The substitution of equations 22 and 23 into 21 gives,

$$p\{V_i + \tfrac{1}{2}\Delta t[Q_i - Q_{PXi} - (C_M + C_P)/B + 2/B(P/\gamma + z - \bar{H})]\} = [m_o + \tfrac{1}{2}\Delta t(\dot{m}_o + \dot{m})]RT \tag{25}$$

which is solved at the end of each increment when an air cavity is present in the conduit. The air flow rate m is not known but is a function of p', given by one of the following:

$$\dot{m} = A_{2i}p'^2 + A_{1i}p' + A_{0i} \qquad 0.528 \le p' \le 1.0$$

$$\dot{m} = MDC = C_{in}A_o(0.686)P_o/(RT_o)^{\frac{1}{2}} \qquad p' < 0.528$$

$$\dot{m} = D_{2i}p'^2 + D_{1i}p' + D_{0i} \qquad 1.0 < p' \le 1.894$$

$$\dot{m} = (-0.686)C_{out}A_op_op'/(RT)^{\frac{1}{2}} \qquad p' > 1.894$$

The solution of equation 25 is then simply a quadratic when one of these forms for m is used. The proper zone of p' is selected in the program and the solution stepped forward. If none of the conditions are satisfied, there is no cavity.

c) Test Runs

Test runs of the program were prepared for two cases: 1) Cedar Bluff Dam outlet works , and 2) Silver Jack Dam outlet works. These are the two sites which are covered by either model or prototype data. The results are shown below. A listing of the code can be found in Appendix II.

1) Cedar Bluff Dam outlet works:

The computer simulation of Cedar Bluff was done using prototype dimensions and a closure rate of 1 ft/min. A comparison of scaled model data and the computer output is shown for air demand during the gate closure, for two levels of imbalance (100% and 60%), figure 28.

2) Silver Jack Dam outlet works:

The computer simulation of Silver Jack was done using prototype dimensions and a closure rate of 0.33 ft/min. A comparison of prototype field data taken during Test 2 and the computer output is shown for air demand during the gate closure, for two levels of head imbalance (100.4% and 66.9%), figure 29.

d) Discussion

The computer code, while still in somewhat of a development stage, provided satisfactory simulations of both problems attempted. The simulation of the Cedar Bluff outlet works compared well with model data acquired in the laboratory study. The simulation of the Silver Jack outlet works was not as good. However, as the coefficient of discharge was lowered so that the partially plugged air intake was more closely simulated, the results moved closer to the actual field measured values. Some work still needs to be done on the code to make it more user friendly and improve I/O. The basic features are coded and have been shown to operate satisfactorily for the two calibration runs.

CONCLUSIONS AND RECOMMENDATIONS

The group of investigations detailed in this report provide additional understanding of the emergency gate closure problem. The model tests furnished data to help predict prototype behavior with good confidence. The prototype tests reiterated these findings and also pointed out some important operation and maintenance considerations. The possibility of modifying the air intake manifold in the downstream gate frame should be reviewed carefully and existing manifolds should be inspected and cleaned. The mathematical model provides the tool needed to evaluate existing and new structures. Based on the math model results, recommendations on air valve sizes and/or conduit reinforcement can be provided. As the end result of these investigations, a standard test was proposed which both checks the gate hoist capacity and operation under unbalanced head conditions, without producing damaging negative pressures in the conduit. This procedure is a simple one and could be done during a regular SEED inspection.

It is recommended that a field test be conducted on an emergency gate with a flat bottom gate leaf, such as the one shown in figure 6, before a standard gate test procedure is adopted for those gates.

Proposed Emergency Gate Test Procedure - Safety of Dams Program

1) Prior to testing, the structure should be reviewed for any possible problems which conceivably could occur due to this test. After the decision to test is made, the computer program should be run and any recommended modifications made. Once the modifications are complete, the test may be performed.

2) The field test would be primarily for determining the adequacy of the gate hoists. A general inspection of the facility should be made to verify the condition of the structure. At this time, the automatic air valve should be inspected, along with the air passages leading to the inside of the conduit. In particular, the manifold plate in the top of

the downstream gate frame should be inspected for clogging. Testing begins with the emergency gate in the closed position and the control gate(s) downstream fully open. The conduit connecting the emergency gate and the control gate(s) should be dewatered.

3) Begin raising the emergency gate, continuing up to a 20 percent opening, while monitoring the hydraulic system pressures. Maintain the 20 percent opening for a minimum of one minute and no longer than two minutes, then close the gate.

This test procedure should include the maximum static loading and frictional forces on the gate leaf. Also within the gate travel specified, the maximum hydraulic downpull due to negative pressures on the gate leaf will be included. It is not recommended that an emergency gate be closed under a fully unbalanced head just for testing purposes. The above test procedure should confirm operation of the hoist mechanism under maximum loading conditions. With proper sizing and maintenance of the automatic air valve and associated vent piping and manifold, no problems would be expected in case of an actual emergency closure.

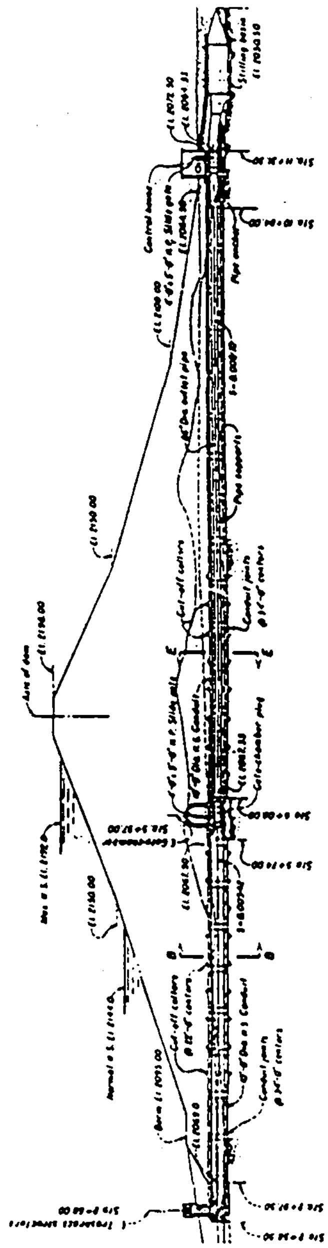


Figure 1: Outlet works layout of Cedar Bluff Dam.

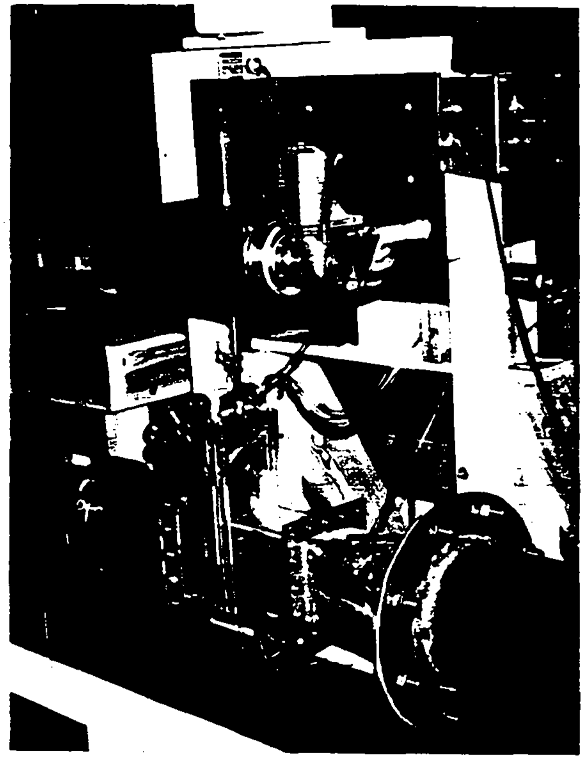


Figure 2: Motor-operated emergency gate in the 1:12 scale hydraulic model of Cedar Bluff outlet works.

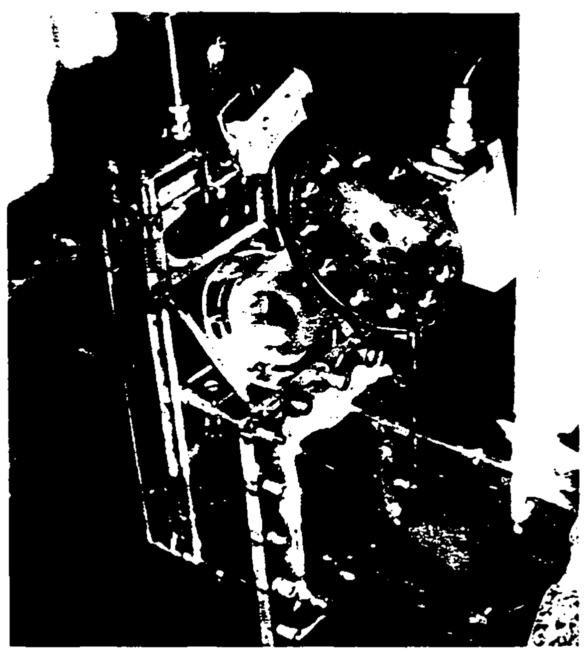


Figure 3: Detail of model air vent configuration, showing the orifice plate.

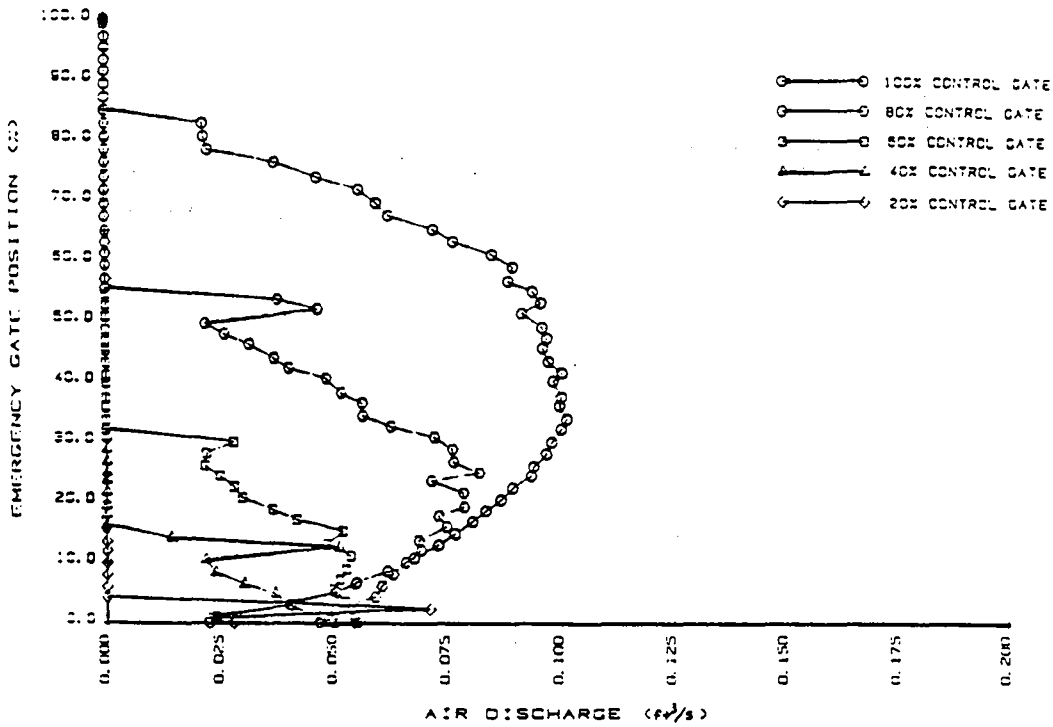


Figure 4: Air demand curves for a 1 ft/min gate closure rate.

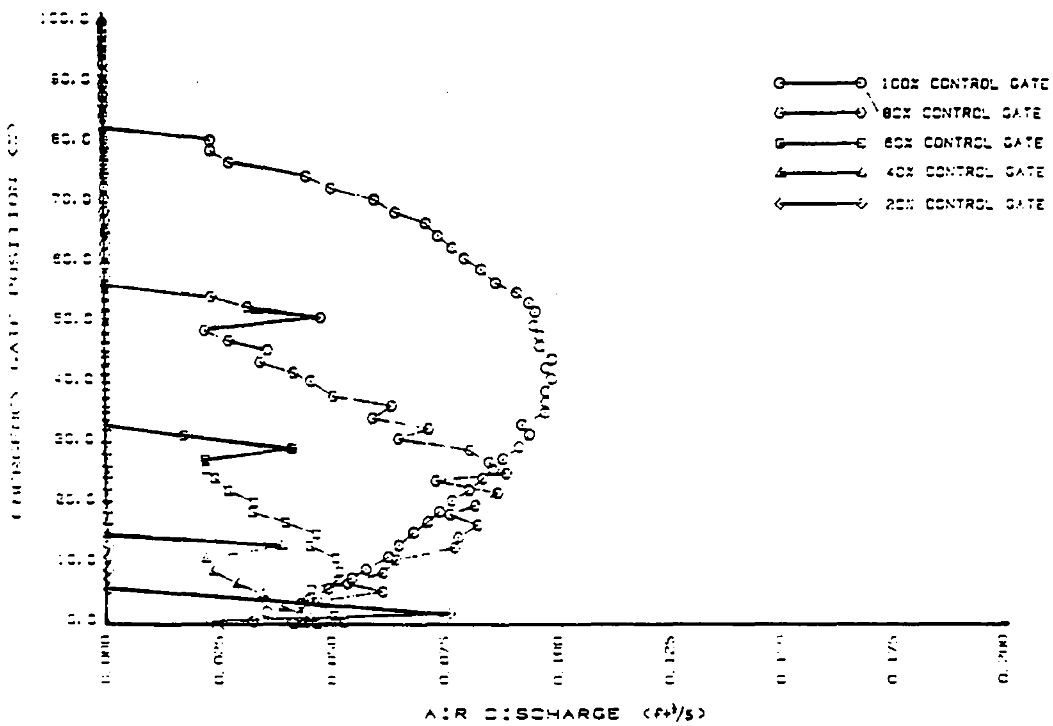


Figure 5: Air demand curves for a 2 ft/min gate closure rate.

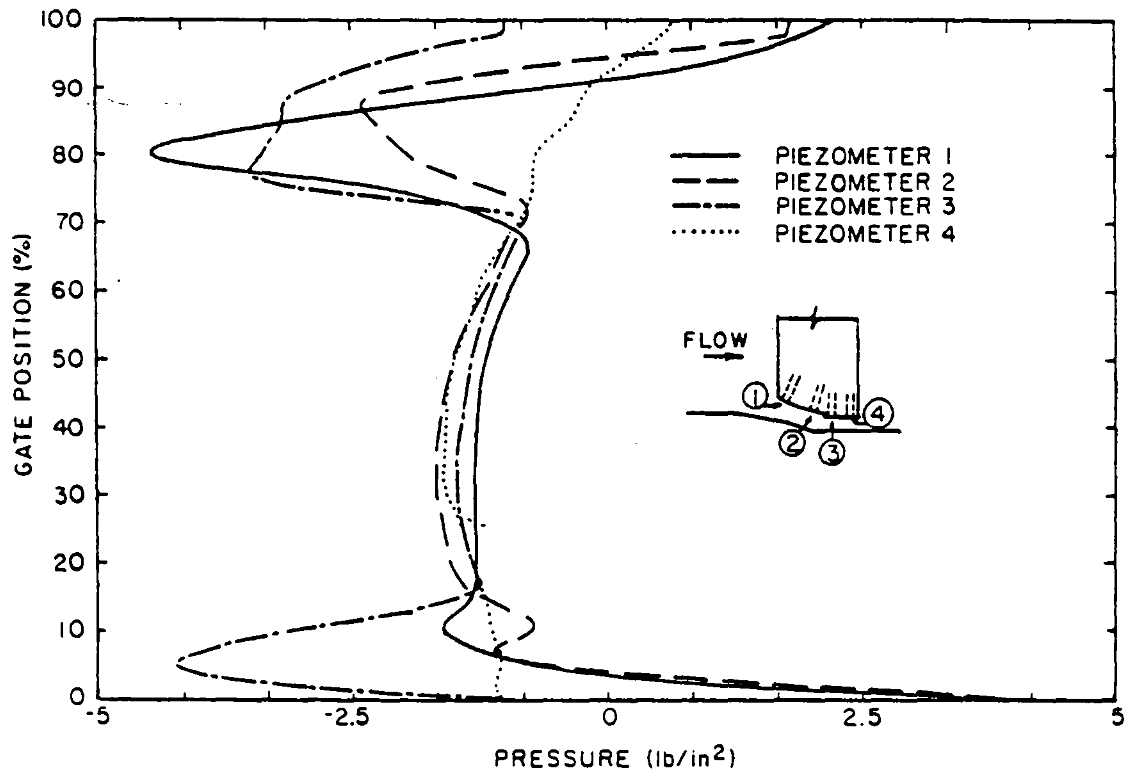


Figure 6: Pressures on the centerline of the gate leaf bottom.

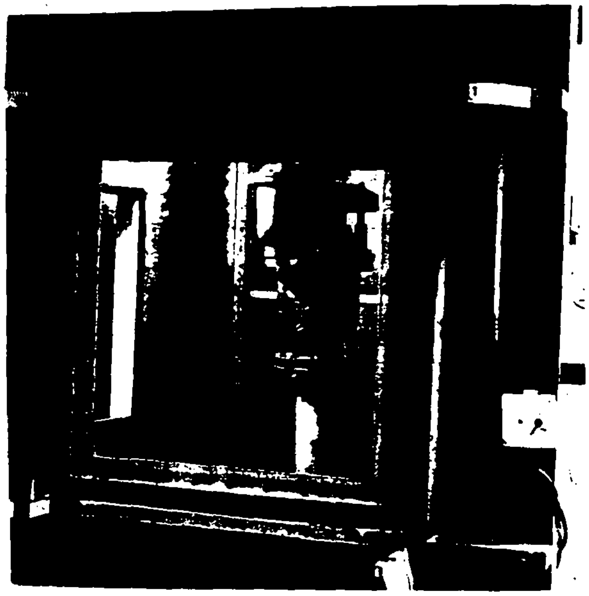


Figure 7: 4 inch automatic air valve in the plenum.

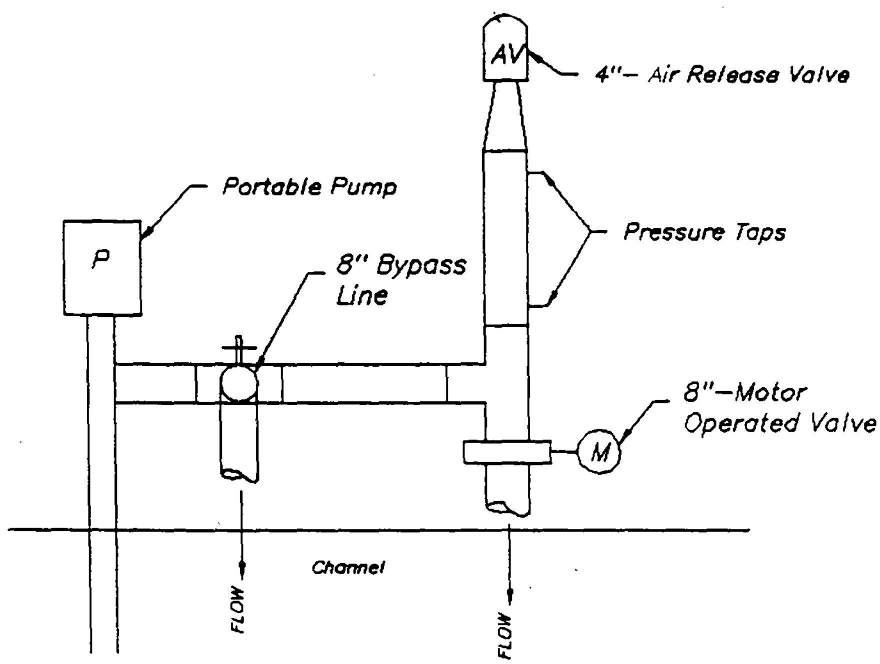


Figure 8: Schematic of the standpipe used to cycle the valve for operational tests.

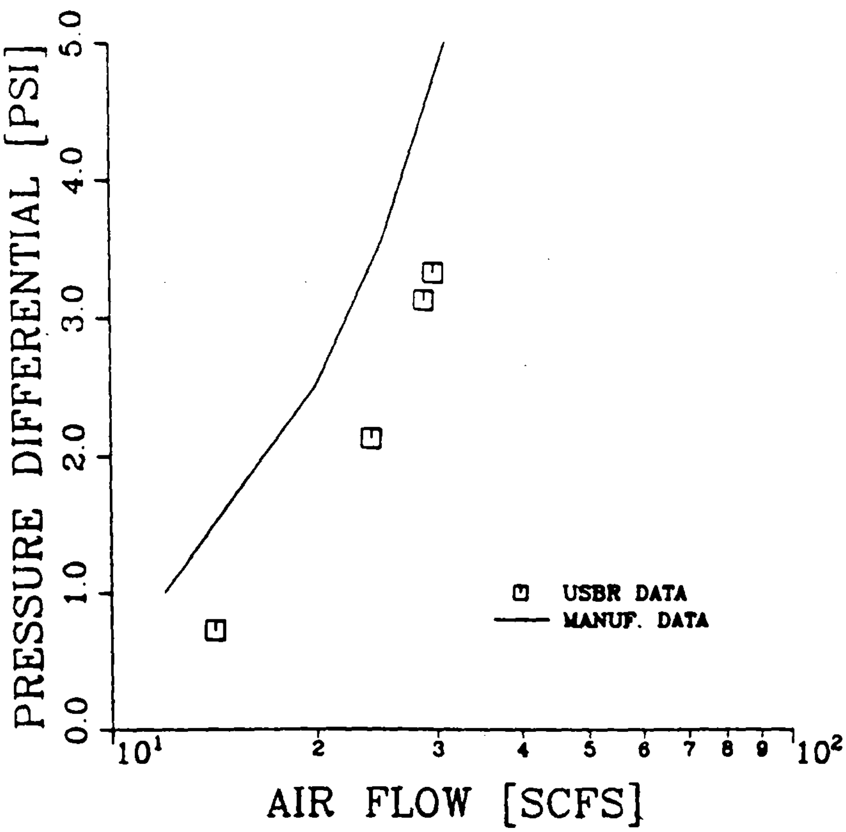


Figure 9: Air valve characteristics, discharge versus pressure differential across the valve.

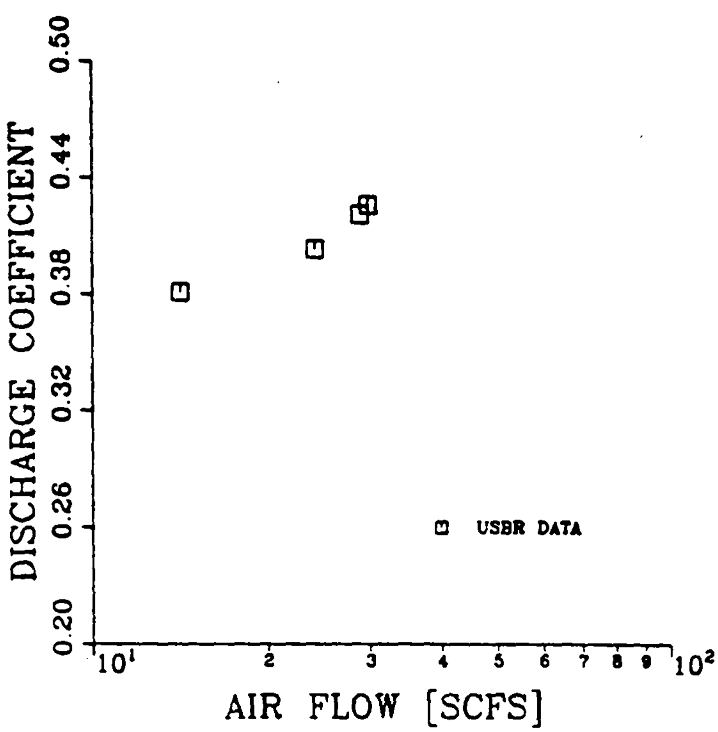


Figure 10: Coefficient of discharge for the 4 inch air valve.

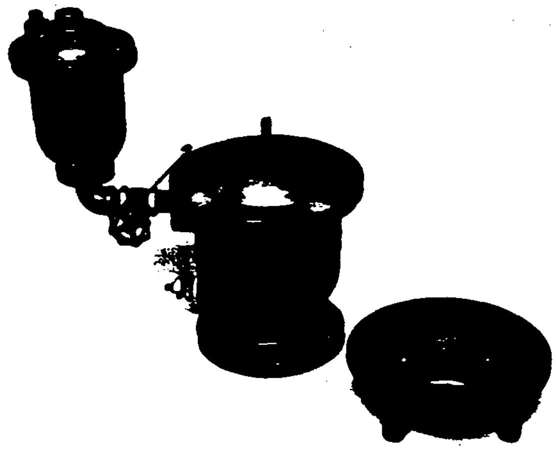


Figure 11: Inside of the air valve after the cycling tests.

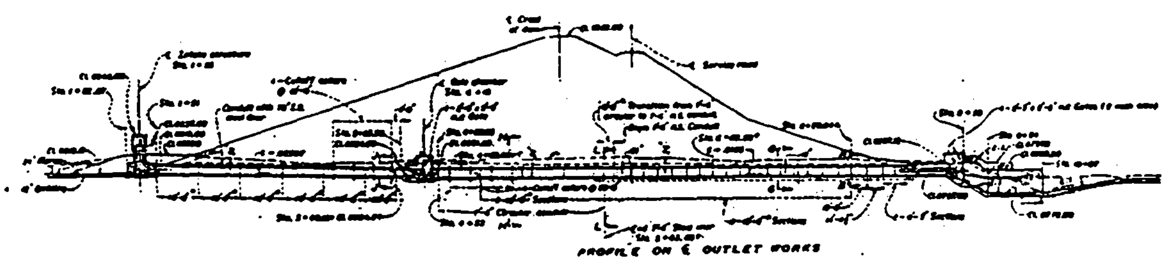


Figure 12: Section of Silver Jack Dam outlet works structure.

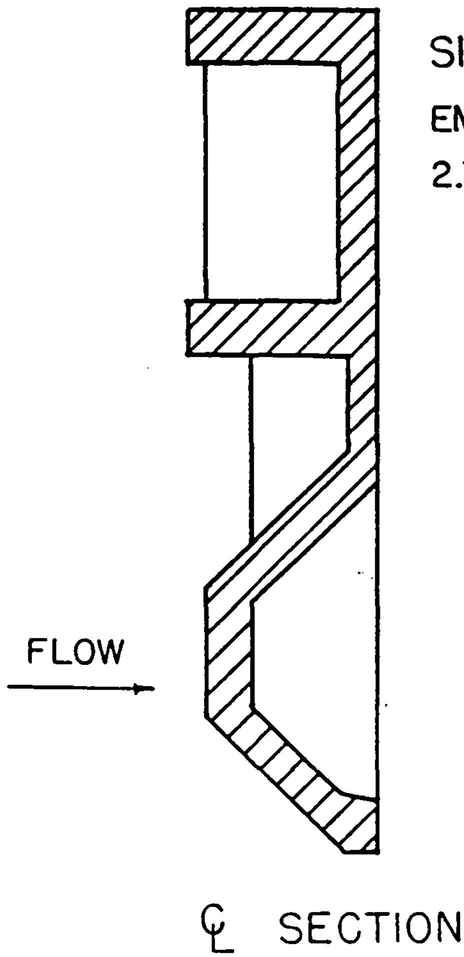


Figure 13: Detail of the emergency gate leaf (no skin plate).

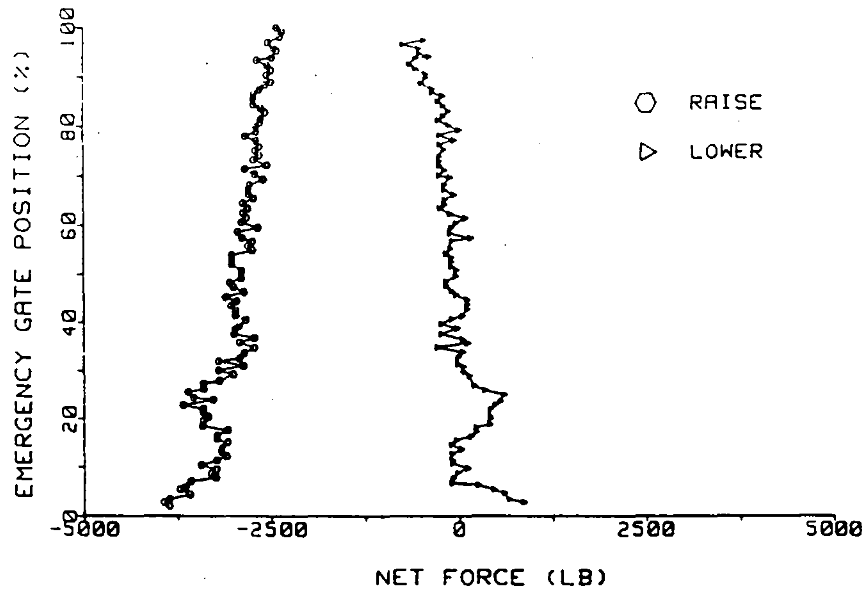


Figure 14: Balanced head test - gate movement in both directions.

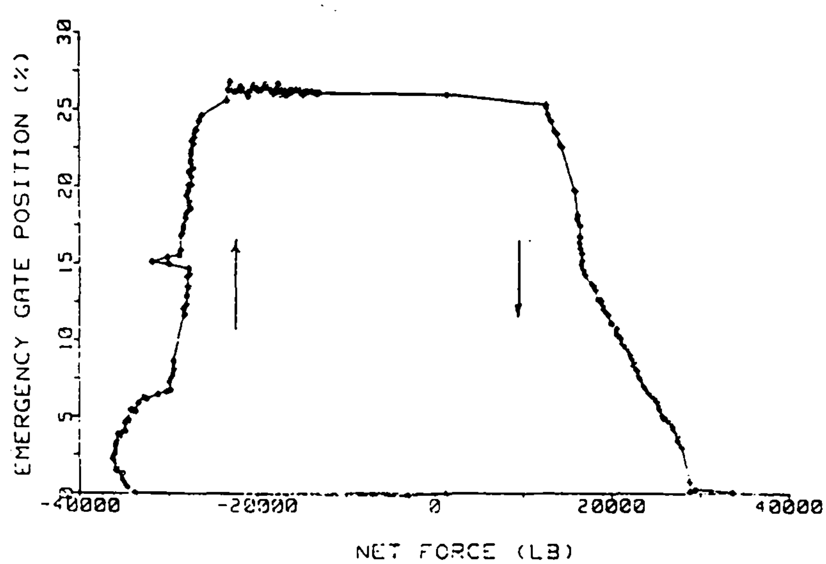


Figure 15: Test results of the proposed standard emergency gate closure test.

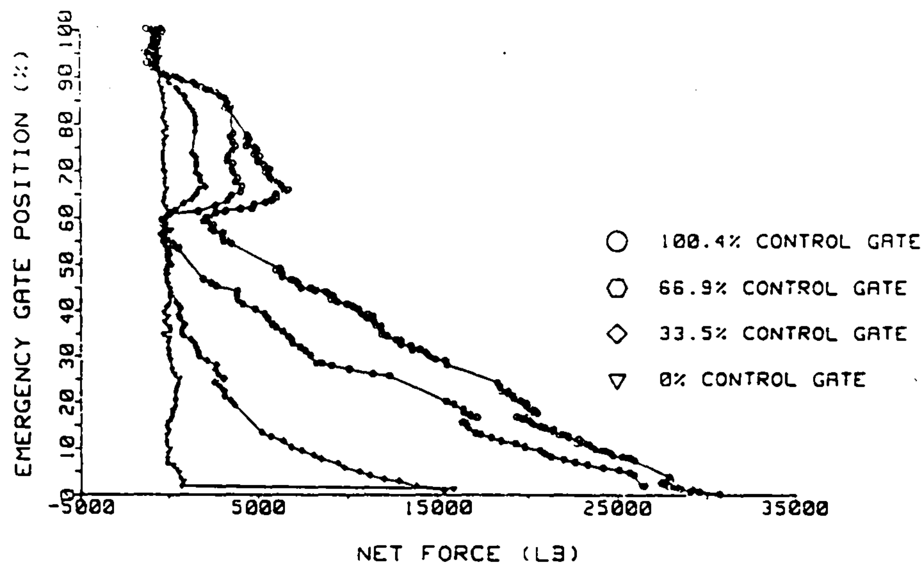


Figure 16: Unbalanced head tests - loading on gate leaf.

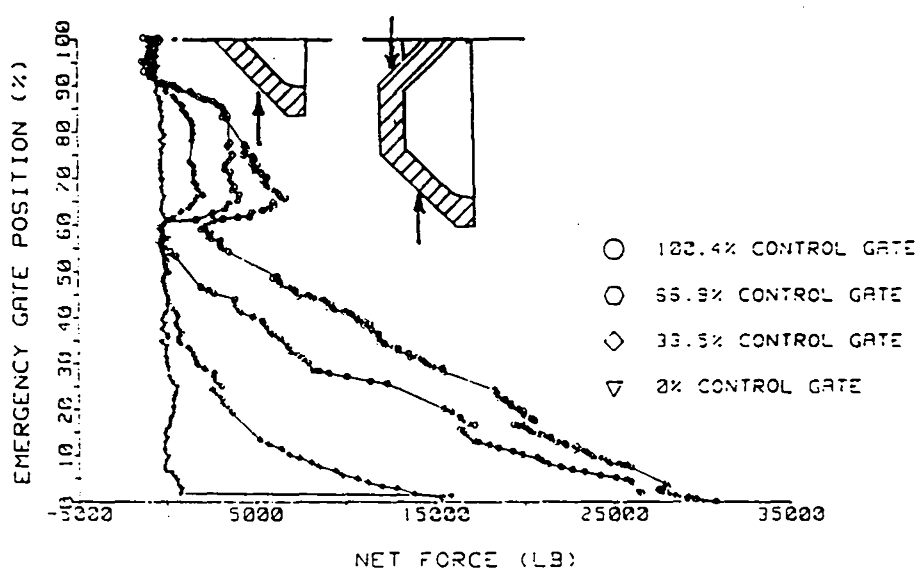
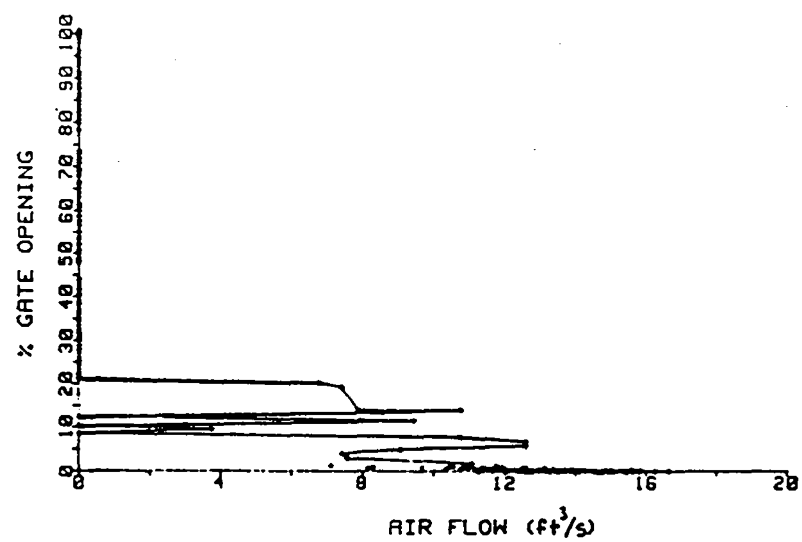
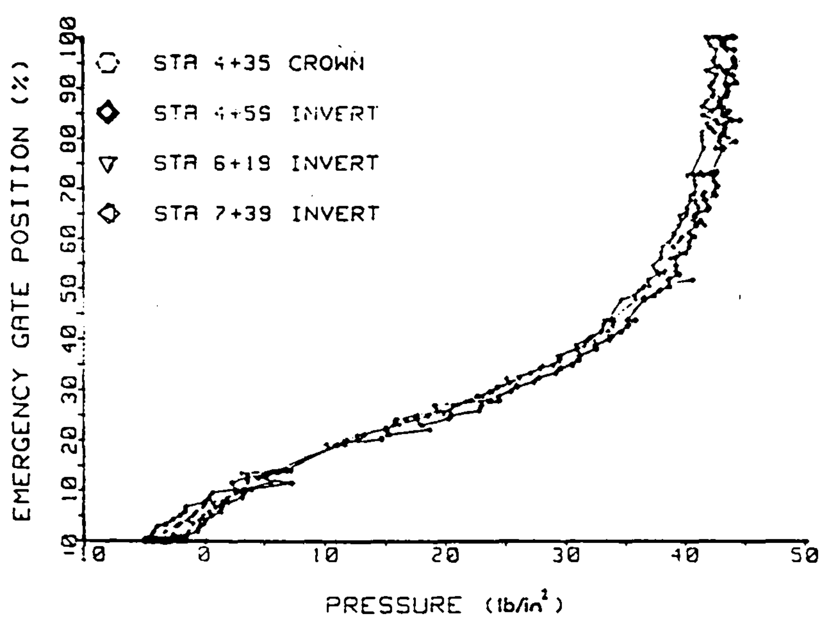


Figure 17: Position of gate leaf relative to gate loading during an unbalanced test.

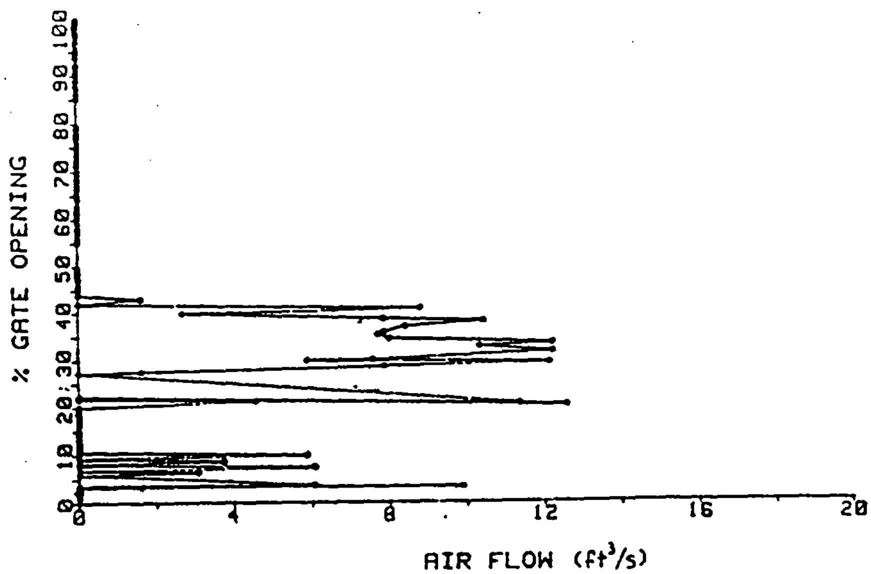


a) Air demand.

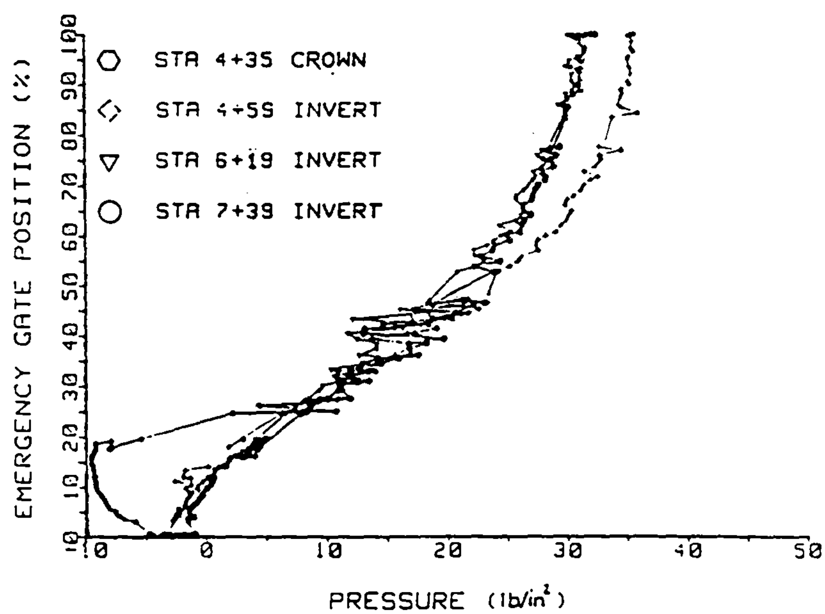


b) Conduit Pressures.

Figure 18: Test Series 1, 25 percent control gate postion.

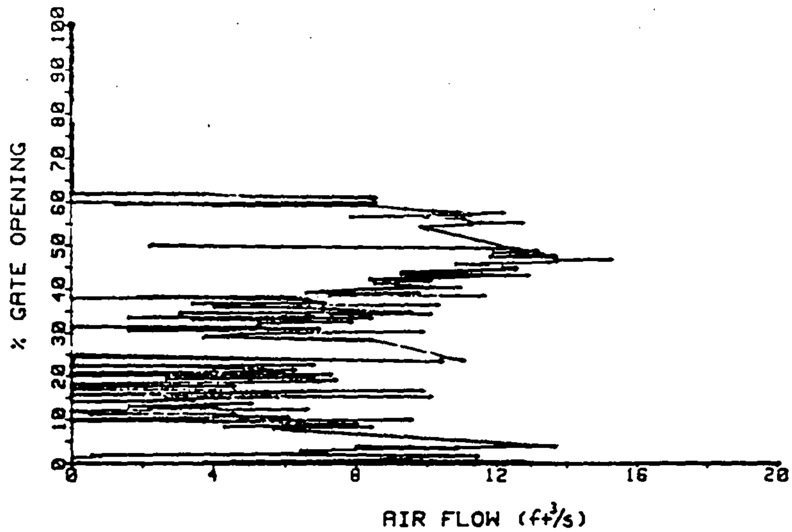


a) Air demand.

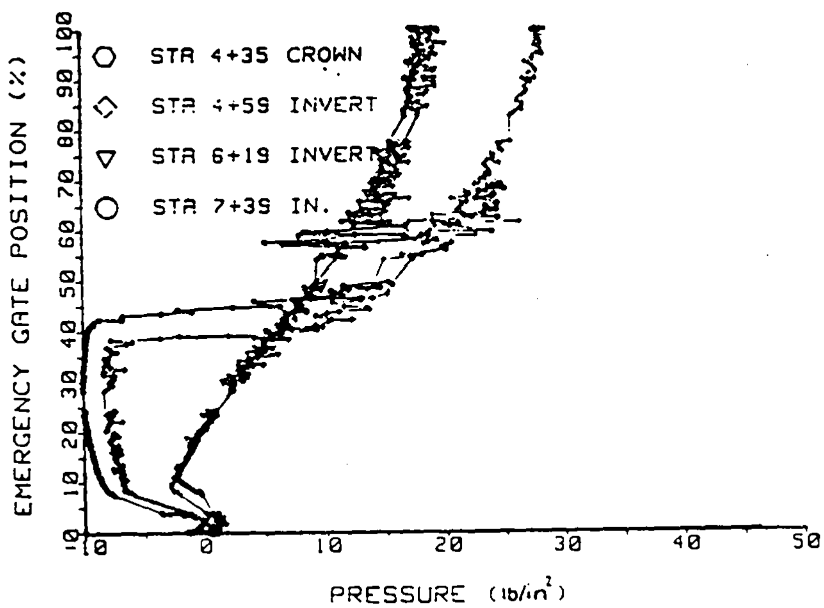


b) Conduit pressures.

Figure 19: Test Series 1, 50 percent control gate position.

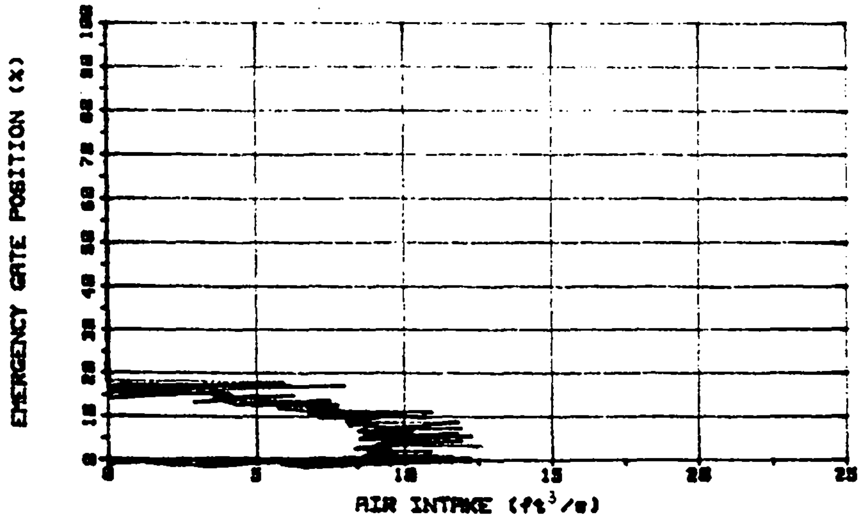


a) Air demand.

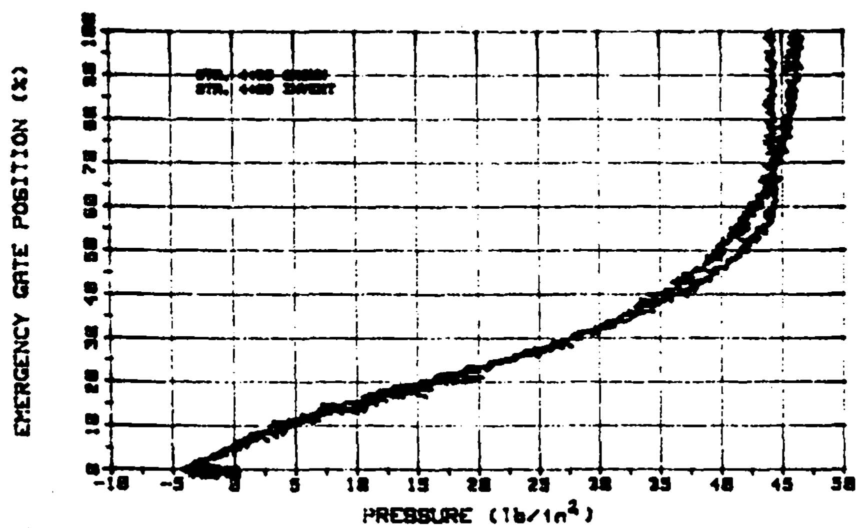


b) Conduit pressures.

Figure 20: Test Series 1, 75 percent control gate position.

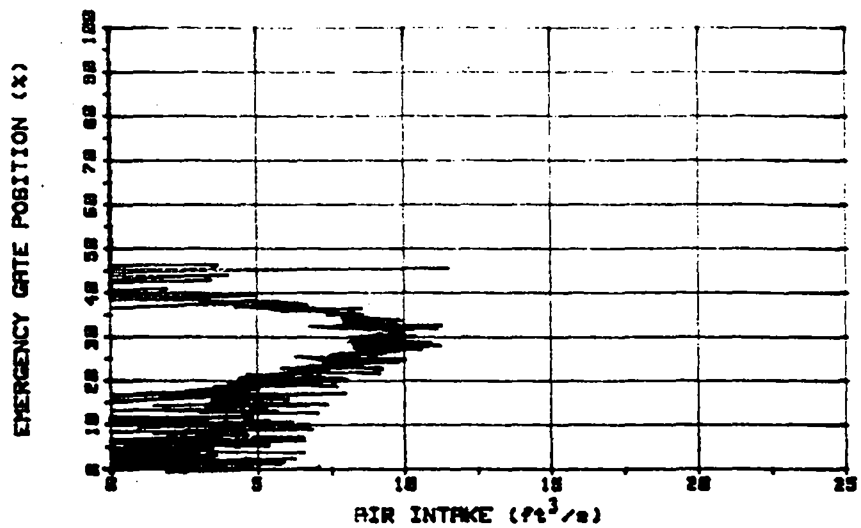


a) Air demand.

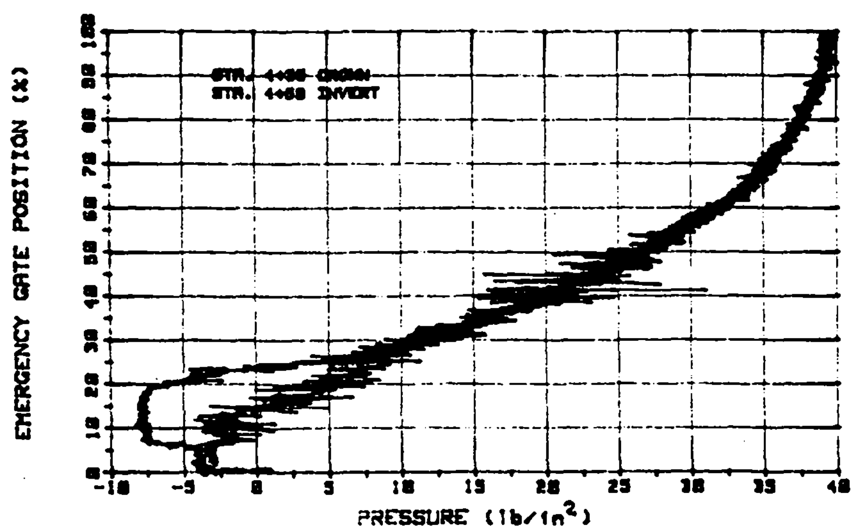


b) Conduit pressures.

Figure 21: Test Series 2, 25 percent control gate postion.

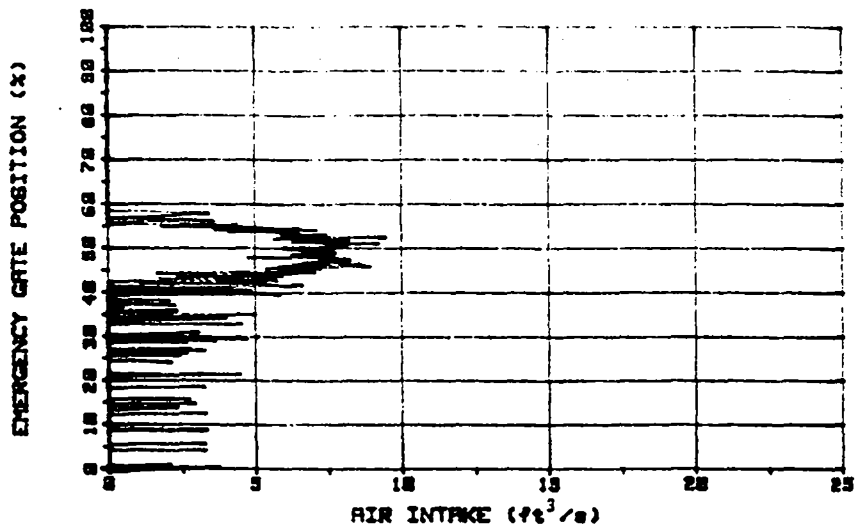


a) Air demand.

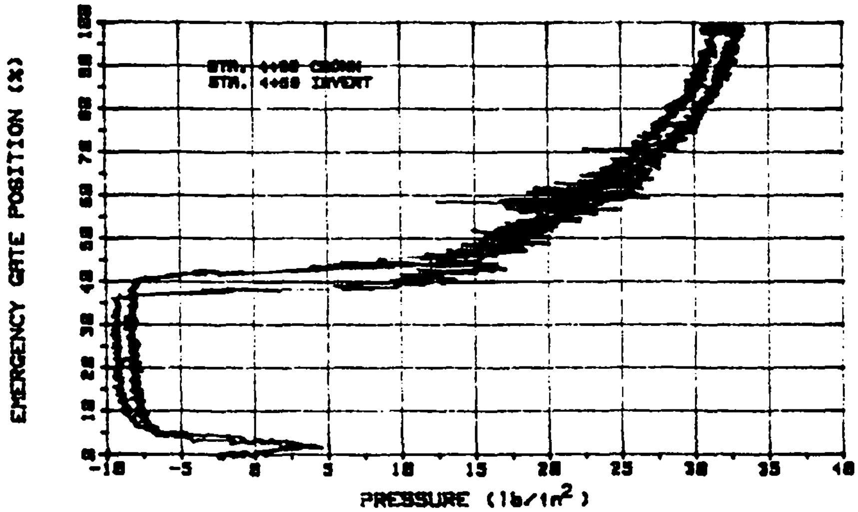


b) Conduit pressures.

Figure 22: Test Series 2, 50 percent control gate position.



a) Air demand.



b) Conduit pressures.

Figure 23: Test Series 2, 75 percent control gate position.

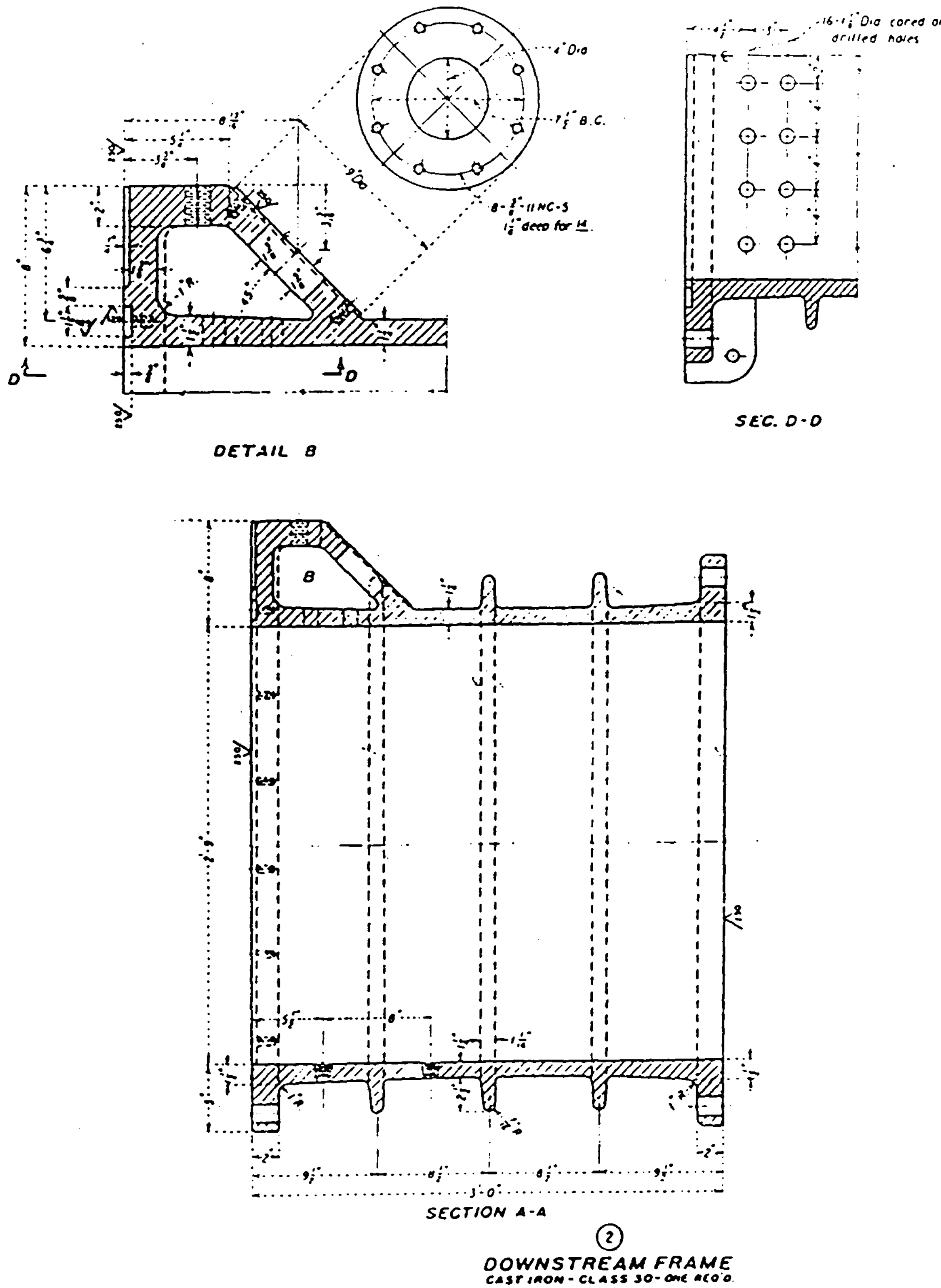
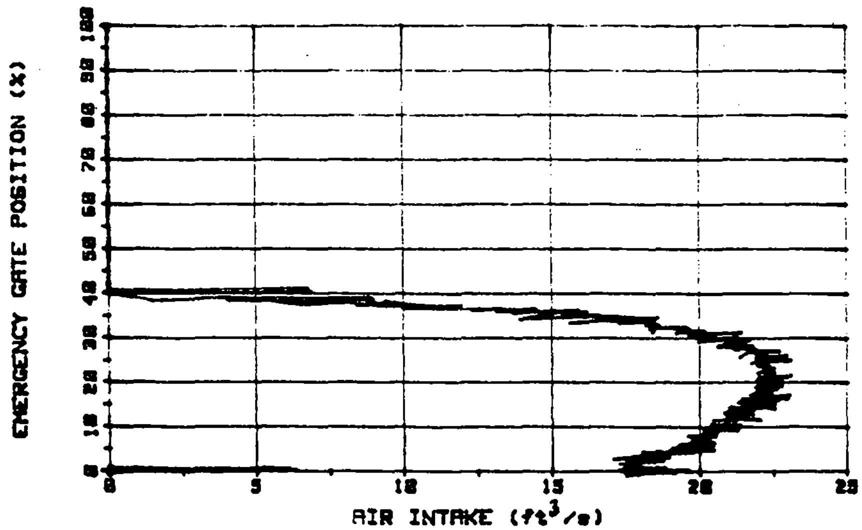
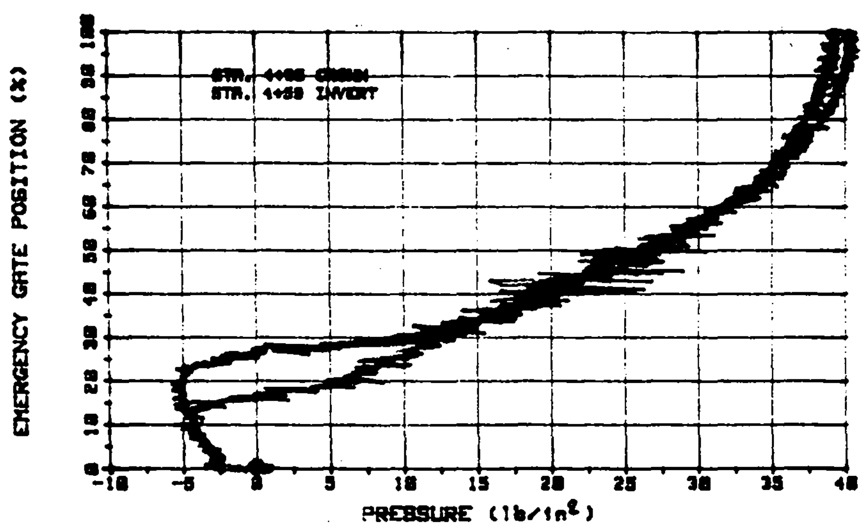


Figure 24: Downstream gate frame with detail of manifold.

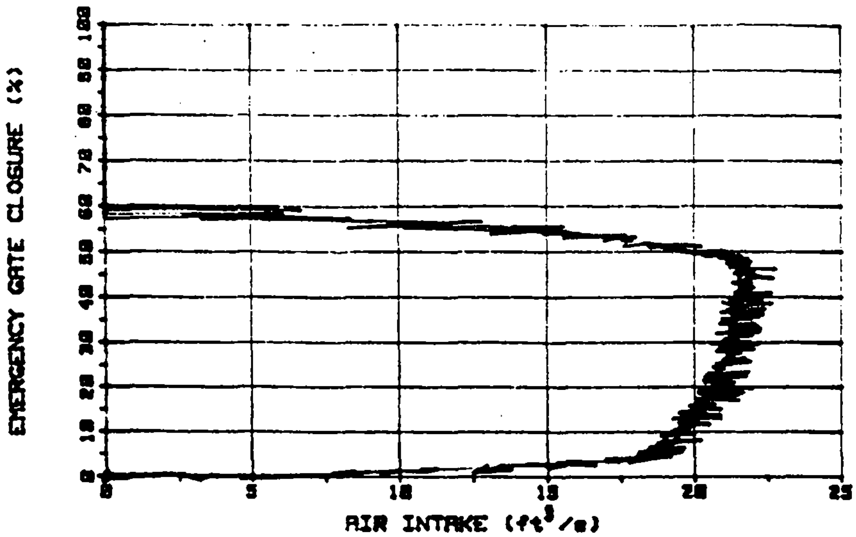


a) Air demand.

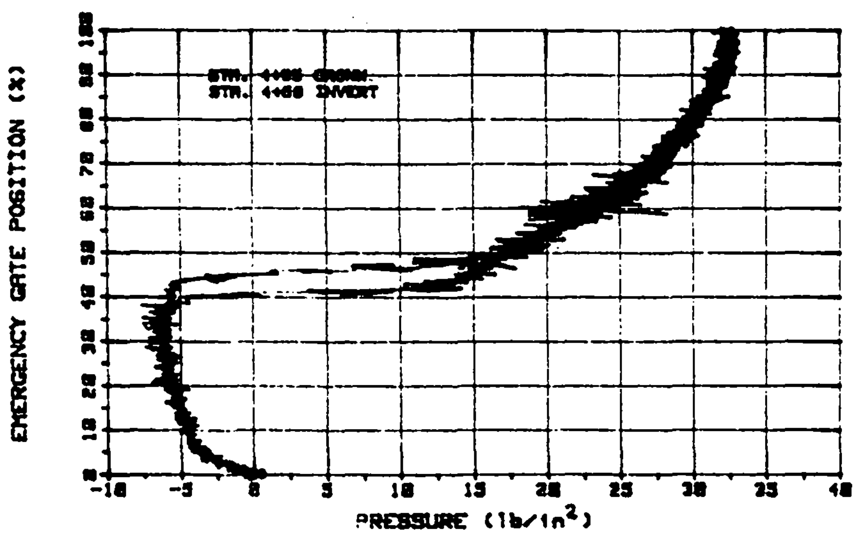


b) Conduit pressures.

Figure 25: Test Series 2, 50 percent control gate position, holes cleaned.



a) Air demand.



b) Conduit pressures.

Figure 26: Test Series 2, 75 percent control gate position, holes cleaned.

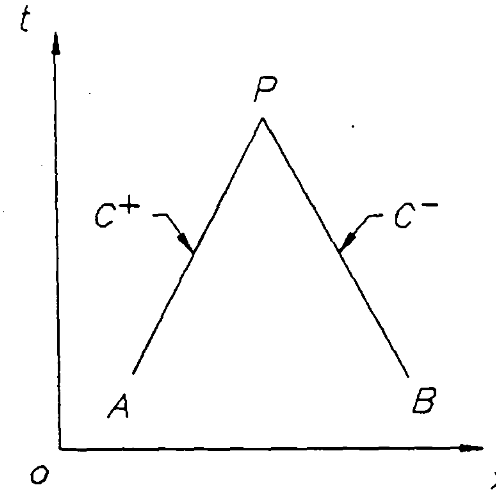


Figure 27: Characteristic lines on the xt plane.

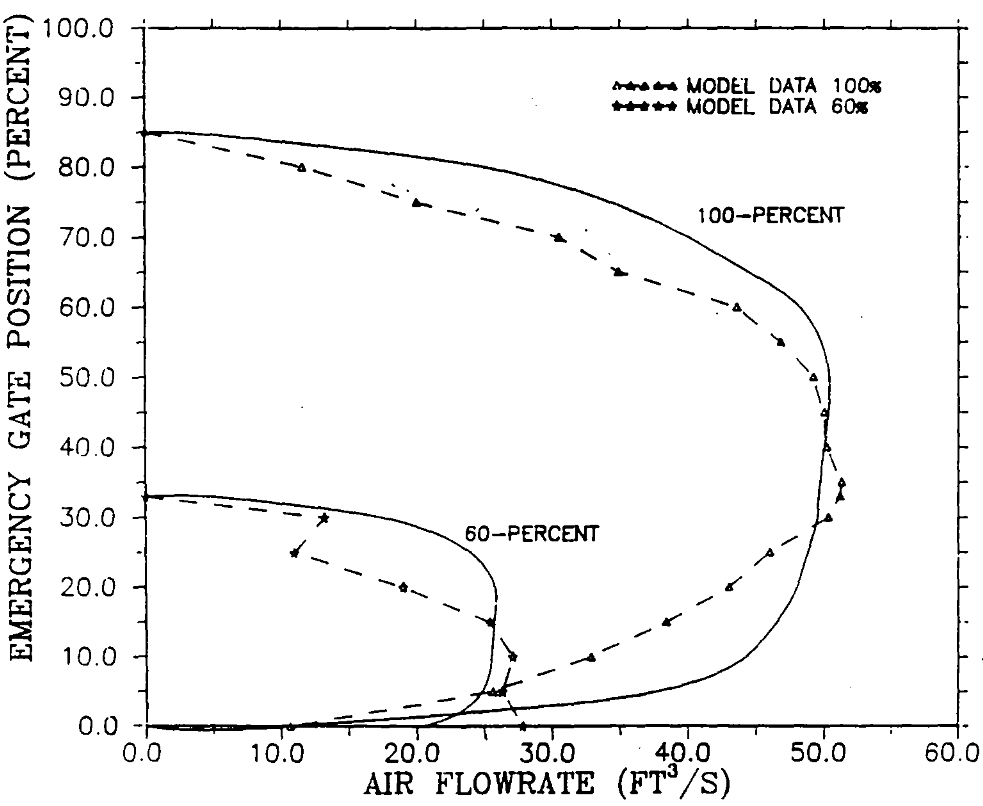


Figure 28: Cedar Bluff Dam, physical model-computer model comparison of air demand during emergency gate closure.

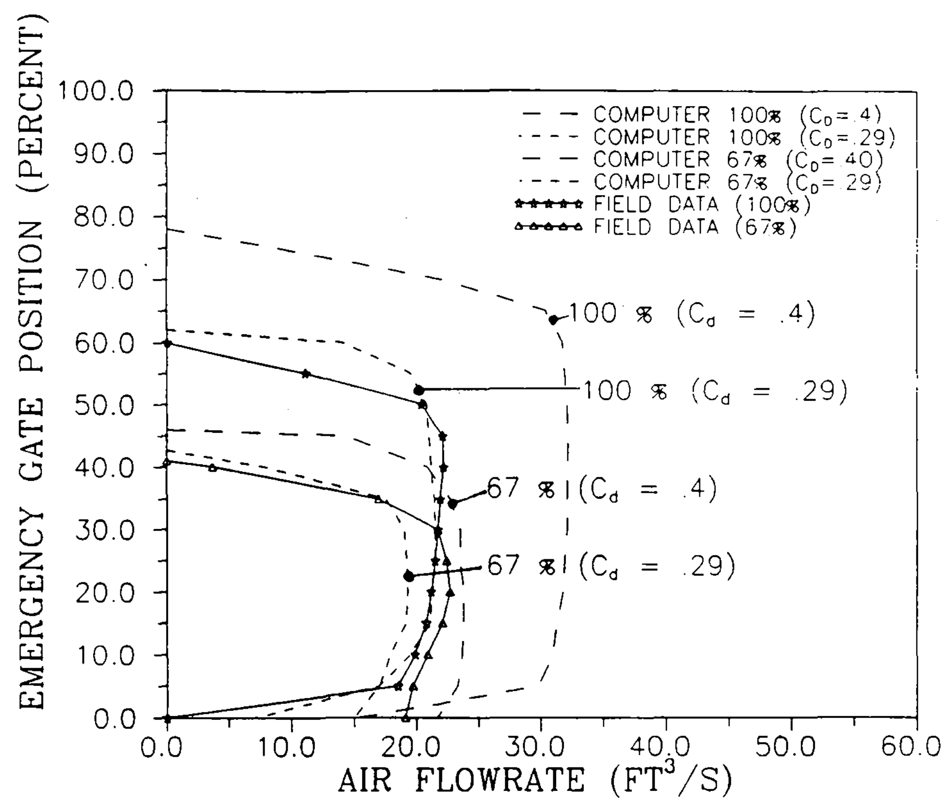


Figure 29: Silver Jack Dam, prototype - computer model comparison of air demand during an emergency gate closure.

APPENDIX 1

Partial List of Symbols

A - pipe area

A_g - open area of gate

B - characteristic impedance

C^+ - positive characteristic

C^- - negative characteristic

C_d - discharge coefficient

C_{in} - air valve discharge coefficient for inflow

C_{out} - air valve discharge coefficient for outflow

D - pipe diameter

H - hydraulic grade line elevation

$\bar{H}$ - barometric head

H_o - steady state head across a gate

H_{Res} - reservoir head

ΔH - instantaneous drop in hydraulic grade line across a gate

Q - volumetric flow rate

Q_o - steady state flow rate

R - Universal gas constant

T - temperature

V - velocity in pipe or volume (as in Eq. 20)

a - acoustic wave speed

f - friction coefficient

g - gravitational acceleration

Symbols (cont.)

m - mass

$\dot{m}$ - mass flow rate

p - pressure in a pipe

p' - p/p_o

t - time

x - distance along a pipe

γ - specific weight of liquid

τ - dimensionless gate opening

APPENDIX 2

Computer Program Listing

```
$DEBUG
C*****************************************************************
C**   MATHEMATICAL MODEL OF AN EMERGENCY GATE CLOSURE UNDER     **
C**     UNBALANCED HEAD CONDITIONS WITH EITHER ONE OR TWO       **
C**                 CONTROL GATES DOWNSTREAM                    **
C*****************************************************************
C**             SOLUTION BY METHOD OF CHARACTERISTICS           **
C**                PROGRAMMED BY K. WARREN FRIZELL              **
C**    SOME PROGRAM SEGMENTS FROM WYLIES' FLUID TRANSIENTS      **
C**                      SEPTEMBER 1987                         **
C**                 HYDRAULICS BRANCH, CODE D-1532              **
C**         DIVISION OF RESEARCH AND LABORATORY SERVICES        **
C**             UNITED STATES BUREAU OF RECLAMATION             **
C**    ENGINEERING AND RESEARCH CENTER, DENVER, COLORADO USA    **
C*****************************************************************
C
C  DATA INPUT CAN BE INTERACTIVE OR THROUGH A DATA FILE
C
C  AIR AOB . AIR INLET VALVE AT CENTER OF 2 REACHES AT EL Z.
C  U.S. RES. EL Z1. Q(NL)=CD*AG*SQRT(2*G*DH).
      IMPLICIT REAL(M)
      DIMENSION Q(3),QP(3),H(3),HP(3),DO(20),D1(20),D2(20),
     1P1(21),AR1(21),AO(20),A1(20),A2(20)
      COMMON /DATIN/F,DX,N,D,QO,DQ,A,OM,TM,Z,ZO,HB,RG,TE,TEO,GAM,G,
     1JPR,CIN,COUT,AO,KIT,NR,NS
      N1=N+1
      R=F*DX/(2.*G*.7854**2*D**5)
      DH=R*QO*QO
      B=A/(G*.7854*D*D)
      DT=DX/A
      HP(N1)=ZO
      ICAV=0
      RTG=RG*TE/GAM
      PO=HB*GAM
      NR1=NR+1
      NS1=NS+1
      DPI=.472/NR
      DPO=.894/NS
      M=.0
      MO=.0
      MDO=.0
      AIR=.0
      QPX=QO
      RHO=PO/(RG*TEO)
      C11=CIN*AO*SQRT(7.*PO*RHO)
      MDC=CIN*AO*.686*PO/SQRT(RG*TEO)
      C12=-COUT*AO*SQRT(7./(RG*TE))
      C13=-COUT*AO*.686/SQRT(RG*TE)
      RT=RG*TE
      C79=DT*(Z-HB)/B
      C81=B*GAM/(PO*DT)
      C84=C81*RT/PO
      Y=.5*DT*C84
      DO 70 I=1,NR1
      P1(I)=(I-1)*DPI+.528
   70 AR1(I)=C11*SQRT(P1(I)**1.4286-P1(I)**1.714)
      DO 72 I=2,NR,2
      A2(I)=(AR1(I+1)-2.*AR1(I)+AR1(I-1))/(2.*DPI*DPI)
      A1(I)=(AR1(I+1)-AR1(I)-A2(I)*(P1(I+1)**2-P1(I)**2))/DPI
      AO(I)=AR1(I)-A1(I)*P1(I)-A2(I)*P1(I)**2
   72 WRITE(6,75)I,A2(I),A1(I),AO(I)
   75 FORMAT(' I,A2,A1,AO=',I3,3E14.4)
```

```
      DO 73 I=1,NS1
      P1(I)=1.+(I-1)*DPO
   73 AR1(I)=C12*PO*P1(I)*SQRT((1./P1(I))**1.4286-1./P1(I)**1.714)
      DO 74 I=2,NS,2
      D2(I)=(AR1(I+1)-2.*AR1(I)+AR1(I-1))/(2.*DPO**2)
      D1(I)=(AR1(I+1)-AR1(I)-D2(I)*(P1(I+1)**2-P1(I)**2))/DPO
      DO(I)=AR1(I)-D1(I)*P1(I)-D2(I)*P1(I)**2
   74 WRITE(6,76)I,D2(I),D1(I),DO(I)
   76 FORMAT(' I,D2,D1,DO=',I3,3E14.4)
      T=.0
      J=0
      V=.0
      DO 11 I=1,N1
      Q(I)=QO
   11 H(I)=(N1-I)*DH+ZO
      HO=H(N)
      WRITE(6,1)
    1 FORMAT('O   T       VOL         MASS         Q1         QPX          Q2
     1   Q3         H1         H2          H3          AIR')
   12 WRITE(6,2)T,V,M,Q(1),QPX,Q(2),Q(3),H(1),H(2),H(3),AIR
    2 FORMAT(1X,F5.2,F9.3,F10.5,7F10.3,F10.6)
Cz*********************************************************************
C***********BEGINNING OF TRANSIENT LOOP********************************
C*********************************************************************
   13 T=T+DT
      IF(T.GT.TM) GO TO 10
C*********************************************************************
C***************U.S. BOUNDARY CONDITION********************************
C*********************************************************************
      HP(1)=RESEL
      QP(1)=(HP(1)-(H(I+1)-B*Q(I+1)+R*Q(I+1)*ABS(Q(I+1))/B
C*********************************************************************
C***************D.S. BOUNDARY CONDITION********************************
C*********************************************************************
      QP(N1)=Q(N)+(H(N)-HP(N1)-R*Q(N)*ABS(Q(N)))/B
C*********************************************************************
C***************AIR VALVE BOUNDARY CONDITION***************************
C*********************************************************************
      HCP=H(1)+Q(1)*(B-R*ABS(Q(1)))
      HCM=H(N1)-Q(N1)*(B-R*ABS(Q(N1)))
      IF(ICAV.EQ.1) GO TO 30
      HP(N)=.5*(HCP+HCM)
      IF(HP(N).LT.Z) GO TO 30
      QP(N)=(HCP-HP(N))/B
      QPX=QP(N)
      GO TO 50
C
C  ESTABLISHMENT OF AN AIR CAVITY.
C
   30 CC=V+.5*DT*(Q(N)-QPX-(HCP+HCM)/B)
      ICAV=1
      C83=C84*(MO+.5*DT*MDO)
      A11=C81*(CC+C79)
      IF(A11.LT.-1..AND.C83.LT..0)GO TO 26
      X=(H(2)+HB-Z)*GAM/PO
      Y1=C83+Y*MDC
      IF(.528*(.528+A11).GT.Y1.AND.Y1.GT..0)GO TO 202
      Y2=C83+Y*C13*PO*1.894
      IF(Y2.GT.1.894*(A11+1.894).AND.-C83/(Y*C13*PO).GT.-A11)
     1GO TO 204
      IF(C83.GT.1.+A11)GO TO 203
      IF(C83.LE.A11+1.)GO TO 201
```

```
      GO TO 26
203   IF(X.LE.1..OR.X.GT.1.894)X=1.3
      KK1=0
      KK=3
      I=(X-1.)/DPO+1
      IF(I/2*2.NE.I)I=I+1
176   SS=1.-Y*D2(I)
      IF(ABS(SS).LT..01)GO TO 82
      S1=.5*(A11-Y*D1(I))/SS
      S2=(C83+Y*D0(I))/SS
178   DIS=S1*S1+S2
      IF(DIS.GT..0)GO TO 86
      I=I+2
      IF(I.GT.NS)I=NS
      KK1=KK1+1
      IF(KK1.LT.KIT)GO TO 176
      WRITE(6,80)
86    PP=-S1-SQRT(DIS)
      IF(PP.LT..0)PP=-S1+SQRT(DIS)
      GO TO 83
82    PP=(C83+Y*D0(I))/(A11-Y*D1(I))
83    I1=ABS((PP-1.)/DPO+1.)
      IF(I1.LT.1)I1=1
      IF(I1.GT.NS)I1=NS
      IF(I1/2*2.NE.I1)I1=I1+1
      KK1=KK1+1
      IF(I1.EQ.I.AND.PP*(PP+A11).GT..0)GO TO 31
      IF(I1.EQ.I.AND.PP*(PP+A11).LE..0)GO TO 26
      I=I1
      IF(KK1.LT.KIT)GO TO 176
      WRITE(6,80)
80    FORMAT('OTROUBLE WITH AIR INLET B.C.')
      IF(PP*(PP+A11))26,26,31
201   IF(X.LT..528.OR.X.GT.1.)X=.8
      I=(X-.528)/DPI+1
      KK=1
      KK3=0
      IF(I/2*2.NE.I)I=I+1
25    S1=.5*(A11-Y*A1(I))/(1.-Y*A2(I))
      S2=(C83+Y*A0(I))/(1.-Y*A2(I))
      DIS=S1*S1+S2
      IF(DIS.GT..0)GO TO 87
      I=I-2
      IF(I.LT.2)I=2
      KK3=KK3+1
      IF(KK3.LT.KIT)GO TO 25
      WRITE(6,80)
87    PP=-S1+SQRT(DIS)
      I1=ABS((PP-.528)/DPI+1.)
      IF(I1.LT.1)I1=1
      IF(I1.GT.NR)I1=NR
      IF(I1/2*2.NE.I1)I1=I1+1
      KK3=KK3+1
      IF(I1.EQ.I.AND.PP*(PP+A11).LE..0)GO TO 26
      IF(I1.EQ.I.AND.PP*(PP+A11).GT..0)GO TO 31
      I=I1
      IF(KK3.LT.KIT)GO TO 25
      WRITE(6,80)
      IF(PP*(PP+A11))26,26,31
202   KK=2
      PP=-.5*A11+SQRT(.25*A11**2+Y1)
      GO TO 31
```

```
 204 KK=4
     S1=.5*(A11-Y*C13*PO)
     PP=-S1+SQRT(S1*S1+C83)
 31  IF(KK.EQ.1)AIR=(A2(I)*PP**2+A1(I)*PP+AO(I))
     IF(KK.EQ.2)AIR=MDC
     IF(KK.EQ.3)AIR=(D2(I)*PP**2+D1(I)*PP+DO(I))
     IF(KK.EQ.4)AIR=C13*PP*PO
     PP=PP*PO
     HP(N)=PP/GAM-HB+Z
     V=CC+DT*HP(N)/B
     IF(V.LT..0) GO TO 26
     M=MO+.5*DT*(MDO+AIR)
     QPX=(HCP-HP(N))/B
     QP(N)=(HP(N)-HCM)/B
     MDO=AIR
     GO TO 50
 26  V=.0
     ICAV=0
     M=.0
     MO=.0
     MDO=.0
     AIR=.0
     HP(N)=.5*(HCM+HCP)
     QP(N)=(HCP-HP(N))/B
     QPX=QP(N)
 50  HO=H(N)
     DO 51 I=1,N1
     Q(I)=QP(I)
 51  H(I)=HP(I)
     MO=M
     IF(J/JPR*JPR.EQ.J) GO TO 12
     GO TO 13
 99  STOP
     END
```