CANAL RADIAL GATE DISCHARGE ALGORITHMS AND THEIR USE

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ABSTRACT

A series of mathematical equations referred to as algorithms have been developed to accurately measure the free and submerged discharge through canal radial gate check structures. The algorithms can be applied to manual and/or automatic flow regulation including mathematical model simulation of canal systems. The results of the laboratory and field verification test programs are briefly summarized and the final series of discharge algorithms are given. The application of the discharge algorithms for measuring or control of flow at the canal radial gate check structure is discussed and a summary is provided.

INTRODUCTION

A typical canal radial gate check structure maintains the upstream water level at or near to the maximum designed flow depth for all flow conditions. The check gate is usually designed to operate at submerged flow conditions. When the flow increases, the downstream water level increases. The head differential across the check gate decreases and usually approaches zero when the canal reaches its maximum designed discharge. Variations of the radial gate opening, the upstream and downstream water levels, the gate lip seal design, and the gate geometry all significantly influence the formation of the vena contracta of the flow jet downstream and, therefore, the coefficient of discharge.

An extensive research program conducted at the Engineering and Research Center Hydraulic Laboratory determined the discharge characteristics for the free and submerged flow conditions for canal radial gate check structures designed and constructed by the Bureau of Reclamation [1].* A 1:6 scale single radial gate hydraulic model placed in a rectangular flume having a horizontal invert was used in the detailed investigation. The variables studied, which were considered critical, are shown on figure 1. The critial variables were the upstream and downstream water levels, HU and HD, the gate opening, GO, the pinion height distance, PH, and the gate lip seal. The gate lip seal was varied by modeling three commonly used designs: (1) the hard-rubber-bar, (2) the music note seal, and (3) without a seal resulting in a sharp edge configuration. The variables held constant were the gate sector radius, the gate width, and the level invert.

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* Numbers in brackets indicate references.

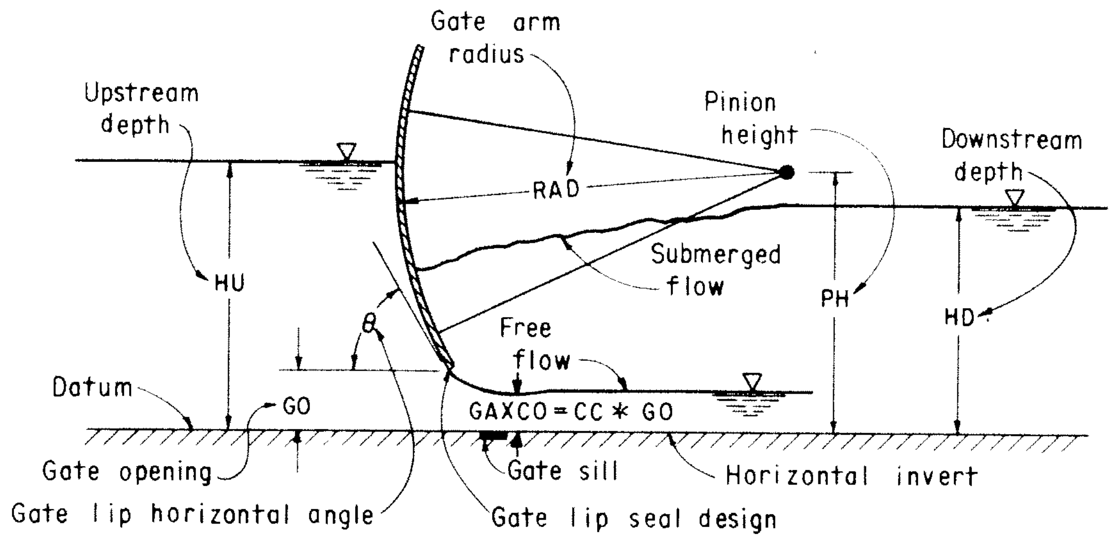


Figure 1. - Variables affecting discharge characteristics of canal radial gates.

MODEL STUDY RESULTS

Experimental data confirmed that Metzler's concept for illustrating the complete discharge characteristics for a canal radial check gate provides the best scheme for developing algorithms [2, 3]. Metzler's concept defines the head term in the general equation for discharge through an underflow gate as the upstream water depth. The general equation can be expressed as:

$$Q = CD*GO*GW*\sqrt{2g*HU} \tag{1}$$

where Q is the discharge through the underflow gate, CD is the coefficient of discharge, GO is the gate opening, GW is the gate width, g is the acceleration of gravity, and HU is the upstream water depth.

The coefficient of discharge, CD, from equation (1), must be associated with the downstream depth, HD, for the submerged flow condition. Figure 2 best illustrates how this association can be achieved. Each data point is plotted with CD as the y-axis coordinate, the upstream depth, HU/PH, as the x-axis coordinate, and the downstream depth, HD/PH, as the z-axis coordinate. The three coordinates for many data points produce a map similar to a topography map. Variations in the water depths and gate geometry are simplified using dimensional analysis employing the radial gate arm pinion height, PH, distance as the geometric reference quantity [2]. A contour mapping process of the submerged flow data points established an orderly family of curves representing even values of the downstream depth, HD/PH, shown as the solid lines on figure 2.

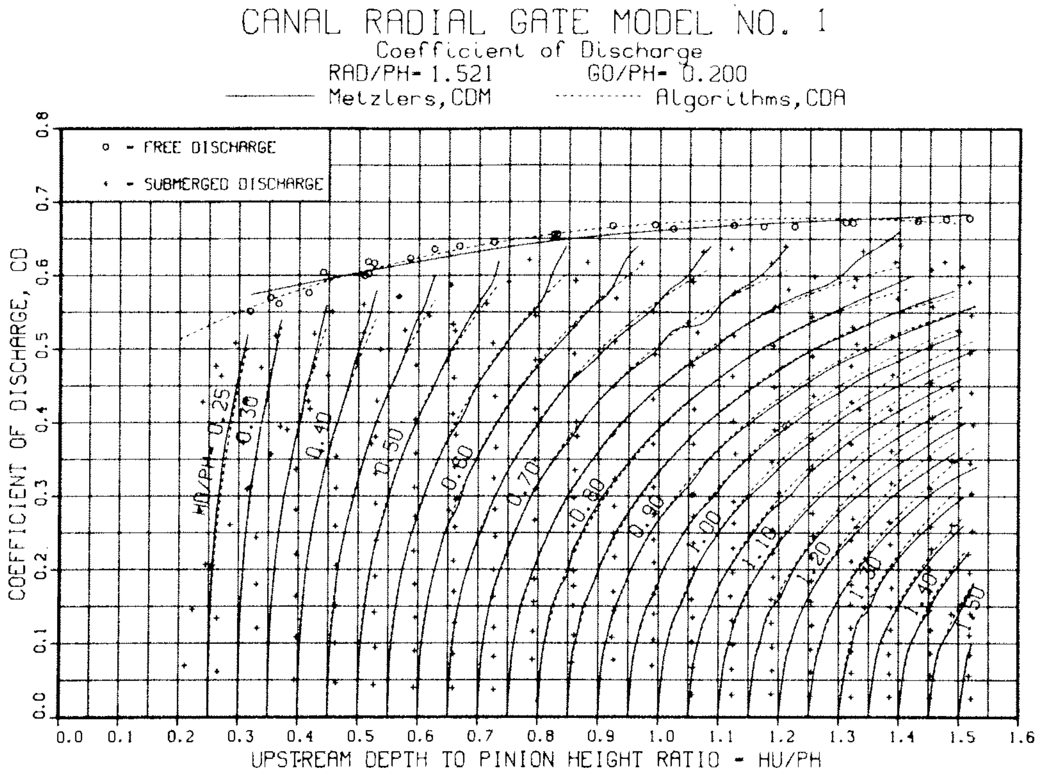


Figure 2. - Example of the coefficient of discharge, CD, map for free and submerged flow conditions based on Metzler's concept.

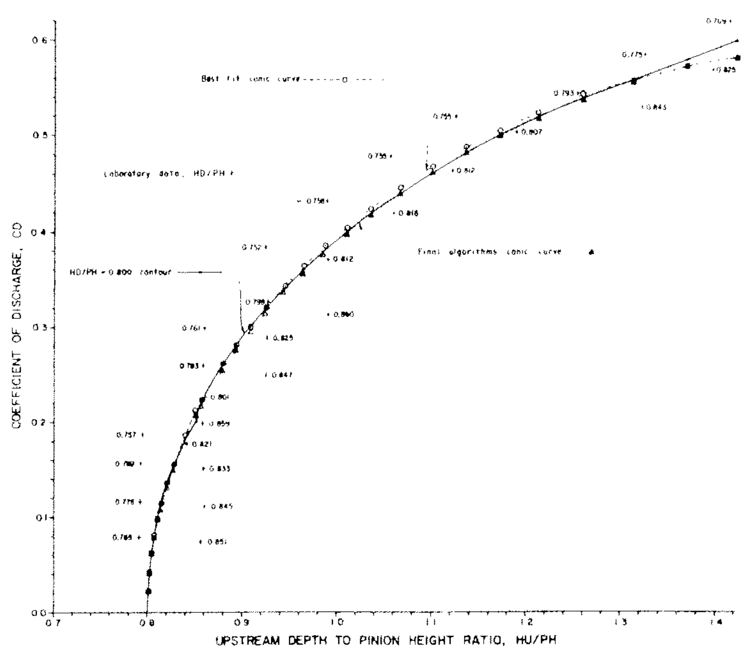


Figure 3. - Illustration of the conic curve application to the submerged flow data at one even contour HD/PH = 0.800.

DISCHARGE ALGORITHM DEVELOPMENT

The submerged flow contours of the downstream depth, HD/PH, have conic characteristics. A conic curve, usually an ellipse, can be fitted to each contour with extreme accuracy. The general conic equation can be expressed as:

$$SCDA = \sqrt{E^2*(D+VX)^2 - VX^2} + FY \qquad (2)$$

where: VX = HU/PH - (HD/PH + E*D/(1.0 + E)) and SCDA is the coefficient of discharge for submerged flow calculated by algorithm, E is the eccentricity, D is the directrix, VX is the horizontal x-axis distance to the focus of the conic curve, and FY is the vertical y-axis distance to the focus.

Application of the general conic equation (2) to one of the even submerged flow contours HD/PH equal to 0.800 taken from figure 2 is illustrated on figure 3. A trial and error process was implemented to determine the E, D, and FY (0.6567, 0.6854, and 0.0, respectively) that would provide the best conic curve fit (dashed line) to the even 0.800 HD/PH contour x and y coordinates. The best fit was based on achieving the smallest actual standard deviation between the conic fit and the contour data. A statistical analysis of the deviation yielded an average error of +0.60 percent and a standard deviation of ±2.25 percent which was considered to be good. Further analysis indicated a conic curve could be fitted to each of the HD/PH contours with the same degree of accuracy. The analysis led to the conclusion that all of the contours have definite conic characteristics. Therefore, the general conic equation (2) was adopted as the basic algorithm to represent the submerged discharge characteristics of the canal radial gate.

The same basic approach was applied to the laboratory data of the free flow conditions except the parameters of the general conic equation (2) are not dependent on the downstream depth, HD/PH.

DISCHARGE ALGORITHMS

The map, figure 2, represents the flow characteristics for a wide range of water levels. However, only one set of gate geometry is illustrated, i.e., one gate lip seal design (in this case, the hard-rubber-bar design), one gate opening, GO/PH, and one gate arm radius to pinion height ratio, RAD/PH. Each variation of geometry requires a new map. Numerous maps were developed from laboratory data. Additional algorithms were derived to vary the constants of the general conic equation (2) as a function of the GO/PH and RAD/PH. The algorithms are based on the gate lip seal having the standard hard-rubber-bar design. An additional algorithm is needed to adjust the coefficient of discharge SCDA when the gate lip seal is of the music note design or when the gate lip has no seal (sharp edge). Experimental data show that the different gate lip seal designs (even a minor modification) can result in a -7 to +12 percent difference in the coefficient of discharge, CD.

The final series of discharge algorithms for free and submerged flow developed from the hydraulic model study are listed in table 1. It

Table 1.- Discharge algorithms for free and submerged flow conditions

Free Flow Algorithms

Eccentricity, FE:

$$AFE = \sqrt{(1.0+(RAD/PH-1.60)^2*31.2)*0.00212} + 0.901$$

$$BFE = \sqrt{(1.0+(RAD/PH-1.635)^2*187.7)*0.00212} - 0.079$$

$$FE = AFE - BFE*GO/PH$$

Directrix, FD:

$$AFD = 0.788 - \sqrt{(1.0+(RAD/PH-1.619)^2*89.2)*0.04}$$

$$BFD = 0.0534*RAD/PH + 0.0457$$

$$FD = 0.472 - \sqrt{(1.0-(GO/PH-AFD)^2)*BFD}$$

Focal Distance, FX1:

IF $GO/PH \leq 0.277$, $FX1 = 1.94*GO/PH - 0.377$

IF $GO/PH > 0.277$, $FX1 = 0.180*GO/PH + 0.111$

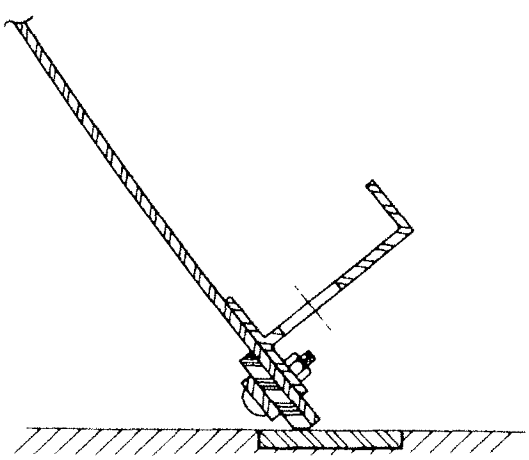
$$FXV = HU/PH - FX1$$

Focal Distance, FY1:

$$FY1 = 0.309 - 0.192*GO/PH$$

Free Coefficient of Discharge

$$FCDA = \sqrt{FE^2*(FD+FXV)^2 - FXV^2} + FY1$$



HARD-RUBBER-BAR

Note: The discharge algorithms listed in this table are based on the gate lip seal of the hard-rubber-bar design as shown above.

Submerged Flow Algorithms

Directrix, D:

$$ADA = 1.0/(11.98*RAD/PH-26.7)$$

$$ADB = -0.276/(RAD/PH) + 0.620$$

$$AD = 1.0/(ADA*GO/PH+ADB)$$

$$BDA = 0.025*RAD/PH - 2.711$$

$$BDB = -0.33*RAD/PH + 0.071$$

$$BD = BDA*GO/PH + BDB$$

$$DR = AD*HD/PH + BD$$

$$D = \left(\frac{1.0}{DR}\right)^{1.429}$$

Eccentricity, E:

$$AEA = -0.019*RAD/PH + 0.060$$

$$AEB = 0.0052*RAD/PH + 0.996$$

$$AE = 1.0/(AEA*GO/PH+AEB)$$

$$BEK = -0.293*RAD/PH + 0.320$$

$$BE = \sqrt{\left(1.0 + \frac{(GO/PH-0.44)^2}{0.7}\right)*0.255} + BEK$$

$$ER = AE*D + BE$$

$$E = \sqrt{\ln\left(\frac{ER}{D}\right)}$$

Vector V1:

$$V1 = \frac{E*D}{1.0+E}$$

Focal Distance, FY:

$$AFA = -0.158/(RAD/PH) + 0.038$$

$$AFB = 0.115*RAD/PH + 0.290$$

$$AF = AFA*GO/PH + AFB$$

$$BFA = 0.0445/(RAD/PH) - 0.321$$

$$BFB = -0.092/(RAD/PH) + 0.155$$

$$BF = BFA/(GO/PH) + BFB$$

$$FY = -AF*HD/PH + BF$$

IF $FY \leq 0.0$, $FY = 0.0$ and $FX = 0.0$

IF $FY > 0.0$, $FX = \sqrt{V1^2 + FY^2} - V1$

$$VX = HU/PH - (V1 + HD/PH + FX)$$

Submerged Coefficient of Discharge

$$SCDA = \sqrt{E^2*(D+VX)^2 - VX^2} + FY$$

should be pointed out that the upstream and downstream water levels, HU and HD, used in the discharge algorithms are based on the normal depth that would occur in a rectangular channel having the same width as the radial gate. Therefore, if the water levels are measured in the canal section (usually trapezoidal in cross section) and if significant head losses occur between the point of measurement and the radial gate, it will be necessary to use the energy balance equations to interface the measured water levels to the respective HU and HD used in the discharge algorithms.

The final submerged flow algorithms (table 1) applied to the even submerged flow contour HD/PH = 0.800 on figure 3 determined the E, D, and FY values to be 0.7058, 0.6094, and 0.0, respectively. The statistical analysis of the deviation between the final algorithms conic curve (dotted line, fig. 3) and the even contour (solid line) produced an average error of -0.70 percent and a standard deviation of +2.78 percent. Figure 2 shows the comparison achieved between the final discharge algorithms (dashed line) and other HD/PH contours.

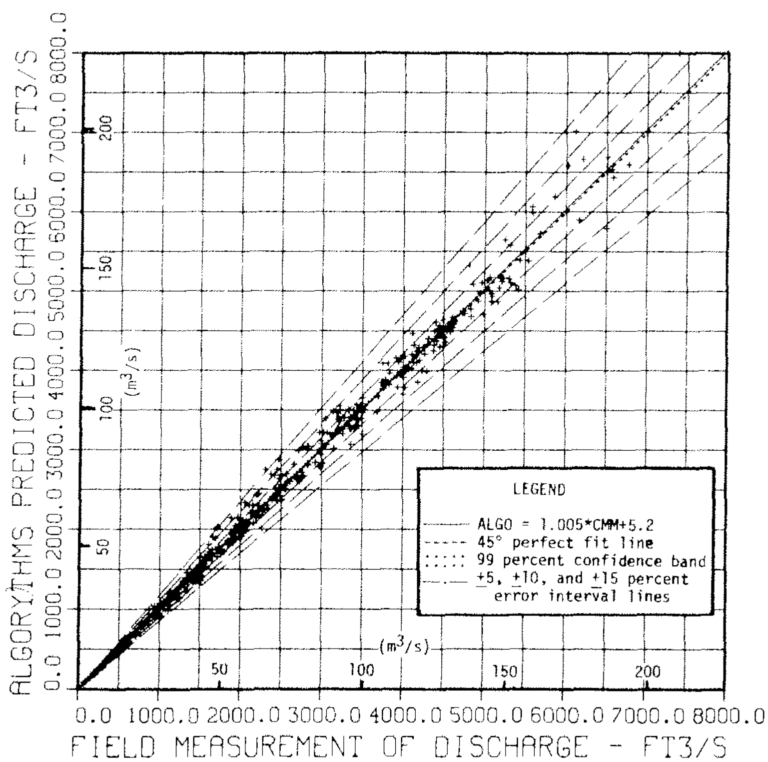


Figure 4. - Comparison of the discharge algorithms predicted, ALGO, and the field measurement, CMM, discharges.

FIELD VERIFICATION

A field verification test program established the degree of accuracy that can be anticipated when the discharge algorithms are applied to the radial gate structures of an operating canal system. Thirteen check structures from seven different canal systems were investigated.

The number of radial gates per check structure ranged from one to five. The flow conditions were submerged at 12 check structures and one was free flow. The discharge algorithms predicted versus the field measurement of discharge for 468 test data points are illustrated on figure 4.

An analysis of the field data yielded an average error of +0.70 percent and a standard deviation of $\pm$4.9 percent. The statistical analysis demonstrated: (a) the distribution of errors is normal, (b) the functional relationship is linear and unbiased, and (c) the algorithms predict the discharge very near to the true value.

APPLICATIONS

A general use computer program has been developed for the practical application of the discharge algorithms [1]. The computer program solves the complex series of discharge algorithms for free and submerged flow conditions. Variations of canal geometry upstream and downstream of the check structure are interfaced through the energy balance equations, and a test to determine if the flow is free or submerged is included.

The general use computer program has an interactive terminal response feature. The watermaster can obtain the gate opening(s) by entering the upstream and downstream water elevations (or depth) and the total discharge, or the total discharge can be determined by entering the opening of each gate by interactive response with a computer terminal. The computer program can also provide a series of rating tables that can easily be used by the ditchrider.

The general use computer program has other applications. The program can be adapted to mathematical models simulating the entire canal system with minor modifications. It could be adapted to a microprocessor-based RTU (remote terminal unit) located at the canal check structure. The RTU could then calculate the discharge and provide an output to a continuous recorder and/or encoder used in a remote monitoring system.

The discharge algorithms can function as a Q controller when adapted to the RTU. A Q controller automatically regulates the gate opening of the check structure to maintain a constant discharge downstream. The discharge algorithms including the energy balance equations would continuously calculate the required radial gate opening(s), to maintain the setpoint discharge, based on real time upstream and downstream water level measurement inputs. A comparator unit would move the gate(s) (raise or lower) whenever the calculated gate opening(s) differ from the actual measured gate opening(s) by more than a prescribed amount.

The application of a Q controller based on the discharge algorithm technique would have its greatest potential use for balancing the operation of an entire canal system being operated by a remote supervisory control system. At the remote control center, the watermaster would determine the desired setpoint discharge setpoint for each check gate structure. The telecommunication system transmits the setpoint discharge to the RTU's located at each check structure. The RTU then changes the gate opening(s) and maintains the new discharge automatically "onsite" based on the real time discharge algorithm process. It is important to understand that a Q controller controls the discharge and not the water levels. Periodic update procedures will have to be incorporated to eliminate the inevitable errors of measurement and calculation. The update procedure provides minor adjustments to the Q controller setpoint discharge to maintain water levels within acceptable limits. Immediate corrections for emergencies or abnormal opertions can be accomplished quickly by simply resetting the discharge setpoint.

SUMMARY

The discharge algorithms accurately represent the complete discharge characteristics for the range of water levels and radial gate geometry normally encountered at canal radial gate check structures. The primary disadvantage of the discharge algorithms is their complexity. Many equations are necessary to achieve the high degree of accuracy. To solve the algorithms efficiently requires a computer program format. Certain skills are required to implement the algorithms and to use the computer program. The algorithms are limited to the characteristics of canal radial gates designed by the Bureau of Reclamation. The canal invert through the radial gate check structure is flat and very near horizontal. The radius to pinion height, RAD/PH, ratio has a range from about 1.2 to 1.7. The maximum water level to the pinion height ratio is about 1.6. The radial gate face plate is flat and smooth. The discharge algorithms listed above are based on the standard hard-rubber-bar gate lip seal design. Correction algorithms are required for different seal designs even when there is a minor modification in the standard design.

The discharge algorithms for canal radial gates should have extensive application. The algorithms, correctly applied, have the capability of being as accurate as any measuring device or procedure available to measure the discharge in small or large canal systems. As a result, a direct benefit is provided for canal operators who control canal systems manually or by remote manual/automatic control systems. The installation of costly Parshall flumes, weirs, acoustic velocity meters, and many canalside turnout meters could be eliminated providing an economic benefit to the project.

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