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Study of sluice gate flow using the finite element method.

C. Y. Li
University of Windsor

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STUDY OF SLUICE GATE FLOW USING
THE FINITE ELEMENT METHOD

A Thesis
submitted to the Faculty of Graduate Studies
in partial fulfilment of the requirements
for the degree of

Master of Applied Science
in the Department of Civil Engineering
University of Windsor

by
C. Y. Li, B.Sc.E,
Windsor, Ontario
March, 1970
ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to Prof. J.A. McCorquodale for patient guidance offered throughout this work, and to Dr. S.P. Chee for helpful advices during this study. The author also wishes to say his thanks to Mr. H. NG, Mr. P. Feimer and Mr. G. Michalczuk.

The author is grateful to Dr. J.F. Leddy, President, University of Windsor and the National Research Council for the financial support given.
ABSTRACT

This paper presents the results of a numerical analysis and an experimental study of the irrotational gravity affected flow under sluice gates.

A finite element procedure is presented for the numerical analysis part of the study. The contraction coefficient, discharge coefficient and downstream water surface profile are the main parameters obtained. The flow field is discretized by triangular elements and the outflow free surface is represented by a portion of an ellipse. The downstream free surface profile is satisfied by choosing the major and minor axes of the ellipse, that minimize the deviation from the constant energy requirement. An iterative successive overrelaxation procedure was used to solve the unknown nodal values of the stream function.

Vertical gates with 0.47 inches thickness for 0°, 15°, 30° gate lips were used for the numerical analysis and experimental study. Vertical gates with 2.0 inches thickness for 15°, 30°, 45° gate lips were also used for experimental study.

It was found that the computer results compare satisfactorily with analytical and experimental data.
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<td>$Q$</td>
<td>Discharge.</td>
<td></td>
</tr>
<tr>
<td>$q$</td>
<td>Discharge per unit width.</td>
<td></td>
</tr>
</tbody>
</table>
Radius of Tainter gate.
Error summation.
Stiffness matrix.
Gate thickness.
Upstream water velocity.
Downstream water velocity.
Constant matrix.
Rectangular coordinates.
Angle of inner gate force with vertical line.
Angle of inner gate force with horizontal line.
Energy functional.
Stream function.
Area of triangular element.
Discrepancy in $C_c$ for $G_i$.
Stream function corresponding to element.
Deviation of energy.
Boundary layer thickness.
Kinematic viscosity.
Over-relaxation factor.
CHAPTER 1

INTRODUCTION

The purpose of this project is the study of gravity flow under sluice gates; this problem has been investigated by a number of researchers using methods which will be described in the next chapter. These methods include conformal mapping, finite differences, infinite series, complex function analysis and a combination of conformal mapping and Riemann-Hilbert.

In channels, the depth-discharge relationships are often determined by the control mechanisms operating within it. There are different kinds of control mechanism, which can indicate what the depth must be for a given discharge and vice versa. One of these control mechanisms is the sluice gate which is discussed here.

Water area at the section downstream from the gate is contracted due to the presence of the sluice gate. The ratio of this contracted area at the downstream section, where the water surface is horizontal, to the water area at the gate opening is called the coefficient of contraction. Once this ratio is known, the water area at the downstream section can be obtained and the discharge of water can be estimated.

The determination of coefficients of contraction for different types of sluice gate lips is a major part of this work. Sharp crested gates and gates with $15^\circ$, $30^\circ$, $45^\circ$. 

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bevelled lips of 0.5 inch thicknesses are studied theoretically and experimentally. Also 15°, 30°, 45° angle gates with 2.0 inch thicknesses are studied experimentally.

The theoretical approach of this work is based on the finite element method, in which the stream functions and coordinates at some selected points in the flow are to be determined. The computer programme for of the finite element method uses an iterative procedure to determine the final answer to the desired degree of accuracy. By adjusting the two parameters Ao and Bo of an ellipse, the downstream surface profile can be determined. The elliptical equation with the Ao, Bo which gives the minimum deviation can be used to express the downstream surface profile and vena contracta.

The experimental results were obtained by measuring the downstream tailwater depth at a sufficient distance downstream from the gate with an electric point gauge. Sets of readings are obtained for different flow conditions and different types of gates.

The experimental and computed results are compared. These are also compared with the results of previous investigators.

The finite element solution assumes no viscosity and no surface tension in the fluid. Also the upstream velocity head is considered in this study. A correction of upstream depth is made at the beginning of the computer programme. The coefficients of contraction and the parameters Ao, Bo are printed out in the computer programme for different heads and different types of gate lips.
CHAPTER 2

SURVEY OF LITERATURE

In 1876, Rayleigh (1) found the solution of the problem of free outflow (i.e. no gravity) from the sluice gate (Fig. 2.1).

The downstream free surface satisfied the equation

\[
\frac{y}{CC} = 1 - \frac{2}{\pi} \sin \theta \quad \ldots \quad (2.1)
\]

where \( \theta \) is the downstream water surface slope \( \tan^{-1} (dy/dx) \), which ranges between 0 and \( -\frac{\pi}{2} \) and \( CC \) is the downstream water depth where water surface is horizontal.

In the corresponding gravity problem, where \( g \) is very large, the equation

\[
\frac{y}{CC} = 1 - \frac{1}{\sqrt{2}} \tan \theta \quad , \quad (\theta < 30^\circ) \quad \ldots \quad (2.2)
\]

can be used; these two equations give nearly the same results.
R. Von Mises (2) dealt with flow under a sluice gate in Fig. 2.2.

He assumed that in the region B, the flow is little affected by gravity, since the acceleration of the flow particles is large there. The free surface of Fig. 2.2 was given by the equation

\[ y = CC - \frac{2DCC}{\pi m} \tan^{-1}(m \sin \theta) \]

where

\[ m = \frac{2DCC}{\beta - CC^2} ; \quad \frac{G}{CC} = \frac{1}{\pi} \frac{2 \tan^{-1} m}{m} \]

G is the gate opening;

\( \theta \) is the angular slope of the profile ..... (2.3)

The first investigator dealing analytically with a sluice gate flow under the influence of gravity appears to have been Pajer (3) in 1937. He assumed an ellipse could be used in the hodograph plane in the conformal mapping method. The fixed free stream line, and the boundary condition of constant pressure were not verified. The resulting line was correct at the end points, and
nearly correct at points in between.

In 1946, Southwell and Vaisey (4) assumed the conditions of Fig. 2.1, where \( D = 12 \) and \( h = 11 \) length units, and the CC calculated from the continuity and Bernoulli equations was 3.854 length unit. The Froude number used was 2.055. They included the upstream free surface and solved the Laplace equation for a sluice gate by substituting a finite difference equation for the partial differential equation and applying a relaxation procedure. In their work, viscosity effects were not taken into consideration. They found \( C_c = 0.608 \) for \( CC/H = 0.312 \).

In 1956, Benjamin (5) made an analysis of the downstream water surface, he divided the profile into two parts by the section B, where the tangent to the surface makes an angle of 25° with the bed (Fig. 2.3). He assumed that downstream of B, the curvature of \( \frac{dy}{dx} \) of the water surface was small, and that all higher derivatives of \( y \) were of rapidly diminishing order. In the region AB this assumption is no longer valid.

An approximate solution was found by taking Von Mises'
solution for the non-gravity case and superimposing on it an allowance for the variation of surface velocity between A and B. The two solutions were fitted together at the section B, the results are given in the following table 2.1.

Table 2.1

<table>
<thead>
<tr>
<th>G/C</th>
<th>0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_0</td>
<td>0.611</td>
<td>0.606</td>
<td>0.602</td>
<td>0.60</td>
<td>0.598</td>
<td>0.598</td>
</tr>
</tbody>
</table>

Perry (6) in 1957 improved the hodograph method by an infinite series method. The pressure can be made constant at a finite number of points by including more terms of the infinite series. In actual application of the mapping, he took a finite number of terms in the series and carry through the complete calculation to find the vertical coordinate of the free streamline y in terms of the N arbitrary coefficients b_i. In practice the numerical work can be reduced somewhat by noting b_0 ≈ 1, and the rest of b_n's are small compared to unity.

Fangmeier and Strelkoff (7) in 1968, avoided using hodograph plane and employed complex function theory to evaluate a nonlinear integral equation for this problem, from which the solution is deduced. They considered fully both the influences of gravity and the upstream free surface, however, their method apparently requires extensive computer time.

In the laboratory, sluice gates are usually sharp edged, because of structure reasons and difficulties of sealing at
complete closure, this is not always practical for field conditions.

In 1933, Mueller (9) made the lip profile elliptical at the entrance and exit sections.

Metzler (9) studied the tainter gate (Fig. 2.4) experimentally. All of Metzler's experimental data corresponded to the constant ratio $r/a = 1.5$, thus his results are not general but apply to that particular geometric condition.

In 1955, Toch (10) made experiments on Tainter gates which covered a substantial range of values of independent variables, both for free and submerged outflow. His results indicated that the coefficient of contraction $C_c$ was determined very largely by the angle $\beta$, as shown in Fig. 2.4, which is the inclined angle at the gate lip, and to a much lesser extent for the ratio $G/Y_1$. It may be convenient to use the following experimental equation to express the coefficient of contraction, obtained by fitting a parabolic curve on the $C_c - \beta$ curve,

$$C_c = 1 - 0.75\beta + 0.36\beta \quad \ldots \quad (2.4)$$

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Where the unit of $\beta$ is taken as $90^\circ$. Equation (2.4) gives results which are accurate to $\pm 5\%$, provided that $\beta \leq 1$.

Southwell and Vaisey (4) also employed a planar inclined gate at an angle $\beta(< 90^\circ)$ to the horizontal as the obstacle (Fig. 2.5). The plane was assumed to have been lowered into the stream to an extent sufficient to avoid standing waves on the downstream side. The relaxation method was used and the angle of $30^\circ$ was taken. The free surface profile can be expressed by the equation (2.5),

$$\frac{Y}{CC} = 1 + \frac{6}{\pi} \left[ \frac{1}{\sqrt{2}} \tanh \left( \sqrt{2} \sin \beta \right) - \sin \beta \right] \ldots (2.5)$$

and they obtained the value of 0.777 for the coefficient of contraction.

In 1969, Larock (11) developed a solution for any arbitrary gate inclination $\beta (0 < \beta < \pi)$, in such a way that an extension to the analytical consideration of curved (radial and Tainter) gates appears feasible. He combined the conformal mapping and
Riemann-Hilbert solution to a mixed boundary condition problem to solve the problem of gravity-affected flow from planar sluice gates of arbitrary inclination.
CHAPTER 3

THEORETICAL STUDY

3.1 Basic Idea of Finite Element Method

According to Zienkiewicz (12), problems of potential distribution in a continuous medium can be solved by using the finite element method. The procedure for solution is summarized as follows:

a) The continuum is isolated by imaginary lines or surfaces into a number of finite divisions or regions.

b) The elements are assumed to be interconnected at a discrete number of nodal points situated on their boundaries. The characteristic values of these nodal points will be the basic unknown parameters of the problem.

c) A function is chosen to define uniquely the state of the dependent variables within each "finite element" in terms of its nodal values.

d) The function now defines uniquely the state of potential within an element in terms of the nodal values. These potentials together with any initial potentials and the characteristic properties of the material will define the state of energy throughout the element and, hence, also on its boundaries.

e) A stiffness or geometric relationship is developed to solve the problem.
3.2 Two Dimensional Formulation

For irrotational, incompressible flow, the two dimensional formulation to specify the energy function is

\[ \chi = \iint \left\{ \frac{1}{2} \left[ \left( \frac{\partial \psi}{\partial x} \right)^2 + \left( \frac{\partial \psi}{\partial y} \right)^2 \right] \right\} \, dx \, dy \]  \hspace{1cm} \text{...(3.1)}

where

\( \psi \) is the unknown stream function, assumed to be single valued,

\( \chi \) is the energy function.

Consider now the region divided into triangular elements. Let the nodal values of \( \psi \) define the function of dependent variables within each element. For a typical triangle ijk (Fig. 3.1),

\[ \psi = \left[ N_1, \, N_j, \, N_k \right] \{ \psi \}^e \]  \hspace{1cm} \text{...(3.2)}

in which

\[ N_i = \frac{a_i + b_i x + c_i y}{2 \Delta} \] etc..

\[ \{ \psi \}^e = \begin{pmatrix} \psi_i \\ \psi_j \\ \psi_k \end{pmatrix} \]

\[ a_i = x_j y_k - y_j x_k \]

\[ b_i = y_j - y_k = y_{jk} \]

\[ c_i = x_k - x_j = x_{kj} \]

\[ 2\Delta = \det \left| \begin{array}{cc} 1 & x_i \, y_i \\ 1 & x_j \, y_j \end{array} \right| \]

\[ = 2 \ (\text{area of triangular } ijk) \]

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The nodal values of $\psi$ now define uniquely and continuously, the function throughout the region. The "functional" $\chi$ can be minimized with respect to these nodal values.

If the value of $\chi$ associated with the element is called $\chi^e$, then we can write

$$\frac{\partial \chi^e}{\partial \psi_i} = \iint \left[ \frac{\partial \psi}{\partial x} \frac{\partial}{\partial \psi_i} (\psi) + \frac{\partial \psi}{\partial y} \frac{\partial}{\partial \psi_i} (\psi) \right] dx \, dy \quad (3.3)$$

Substituting equation (3.2) into equation (3.3)

$$\frac{\partial \chi^e}{\partial \psi_i} = \frac{1}{(2\Delta)^2} \iint \left\{ \left[ b_1, b_j, b_k \right] \psi_i b_1 + [c_i, c_j, c_k] \psi_i c_1 \right\} dx \, dy \quad (3.4)$$

For the element

$$\left\{ \frac{\partial \chi^e}{\partial \psi} \right\}^e = \left\{ \begin{array}{c} \frac{\partial \chi^e}{\partial \psi_i} \\ \frac{\partial \chi^e}{\partial \psi_j} \\ \frac{\partial \chi^e}{\partial \psi_k} \end{array} \right\}$$

\quad (3.5)
Therefore
\[
\left\{ \frac{\partial \chi}{\partial \psi} \right\}_e = \left[ h \right] \cdot \left\{ \psi \right\}_e
\]...
(3.6)

noting again
\[ \int \! dx \, dy = \Delta \]

this leads to the stiffness matrix,
\[
h_{im} = [h] = \frac{1}{4 \Delta} \begin{bmatrix}
    b_i b_i & b_j b_i & b_k b_i \\
    b_i b_j & b_j b_j & b_k b_j \\
    b_i b_k & b_j b_k & b_k b_k
\end{bmatrix} + \frac{1}{4 \Delta} \begin{bmatrix}
    c_i c_i & c_j c_i & c_k c_i \\
    c_i c_j & c_j c_j & c_k c_j \\
    c_i c_k & c_j c_k & c_k c_k
\end{bmatrix}
\]...
(3.7)

The final equation of the minimization procedure requires the assembly of all the differentials of \( \chi \) and the equating of these to zero
\[
\frac{\partial \chi}{\partial \psi_i} = \sum \frac{\partial \chi^e}{\partial \psi_i} = 0
\]...
(3.8)

The summation in equation (3.9) being taken over all elements and nodes i.e.
\[
\frac{\partial \chi}{\partial \psi_i} = \sum \sum h_{im} \psi_m = 0
\]...
(3.9)

where \( m \) is a dummy index.
3.3 Slope Matrix

In some situations the quantity of interest is the gradient of $\psi$. The two components of the gradient can be obtained from equation (3.10).

$$\begin{align*}
\{\text{grad } \psi\} &= \begin{bmatrix}
\frac{\partial \psi}{\partial x} \\
\frac{\partial \psi}{\partial y}
\end{bmatrix} = \frac{1}{2\Delta} \begin{bmatrix}
b_i & b_j & b_k \\
c_i & c_j & c_k
\end{bmatrix} \begin{bmatrix}
\psi_i \\
\psi_j \\
\psi_k
\end{bmatrix} 
\end{align*}$$

..(3.10)
CHAPTER 4

APPLICATION OF FINITE ELEMENT METHOD 
TO THE SLUICE GATE

When flow changes from subcritical \((V<\sqrt{gY})\) to supercritical \((V>\sqrt{gY})\) through a controlled section, the Froude number is the most important governing factor, i.e. this flow is under the influence of gravity. The downstream flow is said to be free, if the issuing jet of supercritical flow is open to atmosphere i.e. it is not submerged by tailwater (Fig. 4.1).

![Diagram](image-url)

**Fig. 4.1**

In this study, the finite element method is used to solve the problem of flow from sluice gates under the influence of gravity.

At the downstream water surface, there are two tangent conditions at points A, B on the outflow water surface profile; one is at the gate lip A and the other is the point B on the downstream water surface where the depth of water is equal.
to the tailwater depth and water surface approaches horizontal. The water surface profile between points A, B is a smooth curve. In general, the direction of flow at the gate lip is tangent to the inner surface of the gate lip which may be vertical or at an angle. The direction of flow at the other point, i.e., where the depth of water is equal to tailwater depth is parallel to the floor. Owing to above characteristics, it is assumed that the profile can be approximated by part of an ellipse equation as shown in Fig. 4.2 and Fig. 4.3.

If the gate lip is vertical and sharp-edged, the profile can be expressed by equation (4.1) and as shown in Fig. 4.2.

$$\frac{x^2}{A_0^2} + \frac{y^2}{B_0^2} = 1 \quad \text{(4.1)}$$

Fig. 4.2

If the gate lip is bevelled, the profile can be expressed by equation (4.2) and as shown in Fig. 4.3.

$$y = (B_0 + CC) - \frac{B_0 \sqrt{A_0^2 - (x-DD)^2}}{A_0} \quad \text{(4.2)}$$
where

\[ CC = G + \frac{P_o^2}{\sqrt{P_o^2 + A_o^2 \tan^2 \beta}} - P_o \]

\[ DD = \frac{A_o^2 \tan \beta}{\sqrt{P_o^2 + A_o^2 \tan^2 \beta}} \]

\[ \beta = 90 - \theta \]

**Fig. 4.3**

The coordinates of the points on the downstream free surface profile are based on equation 4.1 and equation 4.2. The procedure for setting up the finite element method is as follows:

(a) Sketches a few streamlines through the region of interest. Both upstream and downstream boundaries should be located to make sure that the flow at these sections nearly parallel flow as shown in Fig. 4.4.

The upstream free surface is first assumed to be horizontal, and downstream surface is assumed to be elliptical based on equation (4.1) and equation (4.2). Line AB and line EF in Fig. 4.4 are employed as two boundary streamlines.
FIG. 4.4 FINITE ELEMENT MODEL

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The stream function at the upstream, AP, and downstream, DE, boundaries are based on the ratio of the depth to total depth times the total flow.

(b) Several triangular elements are drawn between adjacent streamlines, all the nodes of the elements are located on the approximated streamlines.

(c) The coordinates of each node and the approximate value of stream function ($\Psi$) on each node are determined. The values of stream function ($\Psi$) on the boundary streamlines are assumed to be known.

(d) Substitute the coordinates and the values of the nodal stream functions into the equation (3.9).

$$\frac{\partial \chi}{\partial \Psi_i} + \sum h_{im} \chi_m = 0.$$ \hspace{1cm} (3.9)

where

$$[h] = \frac{1}{2\Delta} \begin{bmatrix} b_1 b_1 & b_j b_1 & b_k b_1 \\ b_i b_j & b_j b_j & b_k b_j \\ b_1 b_k & b_j b_k & b_k b_k \end{bmatrix} + \frac{1}{2\Delta} \begin{bmatrix} c_1 c_1 & c_j c_1 & c_k c_1 \\ c_i c_j & c_j c_j & c_k c_j \\ c_1 c_k & c_j c_k & c_k c_k \end{bmatrix}.$$ \hspace{1cm} (3.7)

If there are $N$ unknown nodes, $N$ simultaneous equations will be obtained.
(e) The extrapolated Liebmann method (13), (14) also known as the 'extrapolated Gauss-Seidal' and 'Successive overrelaxation' method is used to solve these linear simultaneous equations (eq. 3.9), the iterative procedure can be written in the form.

$$U_{\text{new}} = \omega U_L + (1-\omega) \psi$$  \hspace{1cm} \text{(4.3)}

Where $U_L$ is the value calculated by the Liebmann or the Gauss-Seidel method. The parameter $\omega$ is known as the relaxation parameter and for overrelaxation the value of $\omega$ lies between 1 and 2. When a suitable value of $\omega$ is chosen the best rate convergence can be attained. After a certain number of iteration, the value of each unknown differs from its respective value obtained by the preceding iteration by an amount less than a selected tolerance. The calculation for the value of $\psi$ is then complete.

(f) The velocity head of downstream surface elements is calculated in terms of the real value of $\psi$ on each node.

$$\begin{bmatrix}
\frac{\partial \psi}{\partial x} \\
\frac{\partial \psi}{\partial y}
\end{bmatrix} = \frac{1}{2\Delta} \begin{bmatrix}
b_1 & b_j & b_k \\
c_i & c_j & c_k
\end{bmatrix} \begin{bmatrix}
\psi_i \\
\psi_j \\
\psi_k
\end{bmatrix}$$  \hspace{1cm} \text{(4.4)}

$$V_H = \sqrt{\left(\frac{\partial \psi}{\partial x}\right)^2 + \left(\frac{\partial \psi}{\partial y}\right)^2}$$  \hspace{1cm} \text{(4.4b)}
(g) (1) The upstream stagnation point depth was used as the total energy head. Calculate the differences of the energy head and the local energy head (elevation head and velocity head) of each downstream surface elements, then sum the square of the difference of all of the downstream surface elements.

(2) The momentum principle was developed to calculate the downstream total energy head and the same procedure as step (1) was used to obtain the summation of squares of errors.

(h) (1) For different pairs of $A_0$, $B_0$ different summations of squares of errors were obtained. All the summations of squares of errors corresponding to pairs of $A_0$, $B_0$ were plotted on a graph of the major axis of the ellipse vs. the minor axis of the ellipse, and a contour map of summation of squares of errors was acquired. The pair of $A_0$, $B_0$ which are the major and the minor axes of an ellipse, corresponding to the minimum value of summation of squares of errors defines the best outflow curve.

The procedure was repeated and the answer was obtained for different types of gates under different upstream heads.
(2) Besides the contour map method, another method employing a Taylor's series expansion and finite difference method (15) was used. A function was set to express the summation of the square of the energy difference of all the downstream surface elements.

\[ S = \sum \epsilon^2 \]  \hspace{1cm} \ldots(4.5)

This function \( S \) has two parameters \((A_0, B_0)\), the major and the minor axes of an ellipse.

The Taylor's series expansion is as follows:

\[
S(A_0, B_0) = S(A_0, B_0) + S_{A_0}(A_0, B_0)(A_0 - A_0) + S_{B_0}(A_0, B_0)(B_0 - B_0) \\
+ \frac{1}{2} \left[ S_{A_0}^2(A_0, B_0)(A_0 - A_0)^2 + 2S_{A_0}S_{B_0}(A_0, B_0)(A_0 - A_0)(B_0 - B_0) \\
+ S_{B_0}^2(B_0 - B_0)^2 \right] + \ldots \hspace{1cm} \ldots(4.6)
\]

where

- \( S_{A_0} \) is the derivative of \( S \) with respect to \( A_0 \),
- \( S_{B_0} \) is the derivative of \( S \) with respect to \( B_0 \),
- \( S_{A_0}S_{B_0} \) is the derivative of \( S \) with respect to \( A_0 \) and \( B_0 \).

Eliminate the higher derivatives and let \( A_0 - A_{00} = da \), \( B_0 - B_{00} = db \). Then \( \frac{\partial S}{\partial A_0} = 0 \), \( \frac{\partial S}{\partial B_0} = 0 \) are the necessary conditions to make \( S \) to be minimum.

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\[(S_{Ao})_0 + \frac{1}{2} \left[ 2(S_{Ao}, Ao)_o da + 2(S_{Bo}, Bo)_o db \right] = 0 \] \hspace{1cm} \ldots (4.7a)

\[(S_{Bo})_0 + \frac{1}{2} \left[ 2(S_{Ao}, Bo)_o da + 2(S_{Bo}, Bo)_o db \right] = 0 \] \hspace{1cm} \ldots (4.7b)

\[
d a = \frac{\begin{bmatrix} -S_{Ao} & S_{Ao}, Bo \\ -S_{Bo} & S_{Bo}, Bo \\ S_{Ao}, Ao & S_{Ao}, Bo \\ S_{Ao}, Bo & S_{Bo}, Bo \end{bmatrix}}{\ldots (4.8)}
\]

\[
d b = \frac{\begin{bmatrix} S_{Ao}, Ao & -S_{Ao} \\ S_{Ao}, Bo & -S_{Bo} \\ S_{Ao}, Ao & S_{Ao}, Bo \\ S_{Ao}, Bo & S_{Bo}, Bo \end{bmatrix}}{\ldots (4.8)}
\]

The finite difference grid is shown in Fig. 4.5.
Referring to Fig. 4.5, the derivatives in equation (4.8) are expressed as follows:

\[
\begin{align*}
(S_{A_0})_o &= \frac{S_1 - S_3}{2h} \\
(S_{B_0})_o &= \frac{S_2 - S_4}{2hl} \\
(S_{A_0}, A_0)_o &= \frac{(S_1 - S_0) - (S_0 - S_3)}{h^2} \\
(S_{B_0}, B_0)_o &= \frac{(S_2 - S_0) - (S_0 - S_4)}{1^2} \\
(S_{A_0}, B_0)_o &= \frac{(S_5 - S_6) - (S_6 - S_7)}{2h} = \frac{(S_5 - S_6) - (S_6 - S_7)}{4hl}
\end{align*}
\]

An arbitrary pair of \( A_0, B_0 \) was substituted into the finite element programme, a summation of squares of errors \( S_0 \) was obtained. The pair of \( A_0, B_0 \) was shifted to eight surrounding grid points of different pairs of \( A_0, B_0 \) as shown in Fig. 4.5, then these pairs were substituted into the finite element programme, eight additional summations of squares of errors corresponding to eight different pairs of \( A_0, B_0 \) were obtained. Through equations (4.9) and (4.8), \( da, db \) were obtained by using the values of \( S \) of the nine grid points. Set \( A_{0n+1} = A_{0n} + dA_n, B_{0n+1} = B_{0n} + dB_n \).

This procedure was repeated by using the new pair of \( A_0, B_0 \). After several times, the nine grid
points will remain in a certain region. The pair of A₀, B₀ corresponding to the centre of this grid is the correct answer. The only difference between the plane vertical sharp edged gate and the bevelled gate is the assumption of the downstream surface profile. For the sharp edged gate, the assumption of the downstream surface profile is based on the major axis and minor axis of the ellipse which is expressed in equation 4.1 and shown in Fig. 4.2. For the bevelled gate (Fig. 4.3), the assumption of downstream surface profile is based on the angle of the gate lip, the major axis and the minor axis of the ellipse which is expressed in equation 4.2. The rest of the calculation is the same.
EXPERIMENTAL EQUIPMENT

The experimental determination of the coefficient of resistance for sluice gates was carried out in the Hydraulic laboratory of University of Windsor. The tests were made in a 36" high, 36-inch high horizontal flume. The test gate was installed in the grooves on the flume wall and tightened by the clamps on each side. At the downstream side, an electric profile gauge was used to measure the profile of the free surface. The experimental apparatus is shown in Fig. 5.1 and Fig. 5.2.

5.1 Experimental apparatus

5.1.1 Flume set-up

The upstream section of the flume (Fig. 5.2) was connected to an aluminum head tank, which is 5' high, 9' long, 4' wide contracted gradually to the same width as the flume. The end of the flume was connected to a return channel which discharges the water back into the sump. The floor and the frame of the flume are made of aluminum, the walls are made of plexiglass.

5.1.2 Sluice gate set-up

There were four kinds of gates (each 36" high, 18" wide, ½" thick): (a) vertical sharp edged 0°, (b) 15°, (c) 30°, (d) 45° (Fig. 5.3) employed for the first group of experimental tests. Three kinds of gate with increased thickness of 2 inches and with lip angles of 15°, 30°, 45°.
FIG. 5.1 GENERAL LAYOUT OF PROJECT
(Fig. 5.4) were used for another group of experimental tests. The angle indicates the deviation between the upstream face of the gate lip and vertical.

The gate was sealed with plasticene to prevent the leakage and was tightened by a long clamp on both sides at the top of the flume.

The gates are shown in Photo (5.1) and Fig. 5.3 and Fig. 5.4.

5.1.3 Auxiliary equipment

(a) The centrifugal pump used in the experimental study has a maximum speed of 1450 R.P.M., a minimum speed of 1100 R.P.M., a maximum head of 22 ft. and a maximum discharge of 3500 U.S.G.P.M.

(b) The electric point gauage (Photo. 5.2) was employed to measure the depth of downstream water surface and downstream surface profile.

(c) The magnetic flow meter (Photo. 5.3) was used to measure the steady discharge through the sluice gate.

(d) A baffle to dissipate turbulent fluctuations in the head tank was placed 25" upstream from the end of contracted tank as shown in Fig. 5.2.
FIG. 5.3 TEST GATE WITH 0.47 IN. THICKNESS
FIG. 5.4 TEST GATE WITH 2.0 IN. THICKNESS
PHOTO 5.1.a TEST GATE OF 15° AND 30°
PHOTO. 5.1.b TEST GATE OF 45°
PHOTO. 5.2 ELECTRIC POINT GAUGE
PHOTO. 5.3 MAGNETIC FLOW METER
5.2 Experimental Procedures

5.2.1 Downstream water surface profile measurement

For each type of gate, the profile was determined as follows:

(a) The gate opening was measured and recorded. The reference reading by using the electric point gauge to measure the downstream water depth was read and recorded before the flow was run.

(b) The pump was then started and water was delivered to the contracted head tank which is shown in Fig. 5.1 and Fig. 5.2. Different flow rates (Q) corresponding to different upstream heads were run. The magnitudes of flow rates were read and recorded from the magnetic flow meter; the upstream heads were read from the scale on the wall of the flume and recorded.

(c) The electric point gauge was placed at several sections downstream from the gate to measure the depth of water. The maximum, the minimum and the estimated average readings were read and recorded at each station.

(d) The experiment was repeated for all gate types.

5.2.2 The measurement of coefficients of contraction

The step in measuring the coefficient of contraction
are described as follows:-

(a) The same procedures described in the section a and section b above were performed.

(b) The electric point gauge was moved downstream to a sufficient distance from the gate. At a section where the depth of water is almost the same as the tailwater depth and almost parallel flow, the maximum, the minimum and the estimated average readings were obtained and recorded. The readings were taken at the place where the water surface is nearly flat across the flume (i.e. no side effects).

(c) A set of readings was obtained for each different upstream head.

(d) After completing one type of gate, the above procedures were repeated by another type of gate.
The first step of the numerical method is the drawing of the flow pattern and triangular finite elements on graph paper. Then the coordinates and the estimated values of stream function $\psi$ for all the nodes are set. Approximate initial values of $A_o$ and $B_o$ are selected for use in the computer programme.

Some of the parameters which were used in the computer programme are shown in Table 6.1.

Table 6.1 Some Parameters Used in the Numerical Solution

<table>
<thead>
<tr>
<th>Gate opening $G$ (in.)</th>
<th>Tolerance of the value of $\psi$ ($\text{in}^2/$sec)</th>
<th>Gate thickness $t$ (in.)</th>
<th>U/S head $D$ (in.)</th>
<th>$\omega$</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.0001</td>
<td>0.47</td>
<td>24.0</td>
<td>1.2</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15.0</td>
<td>1.1</td>
<td>,30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.1 Computed Coefficients of Contraction ($C_o$)

The coefficients of contraction for both the energy method and momentum method were computed in the computer programme.

All the computed values of $C_o$ are shown in Fig. 8.1 to Fig. 8.6 and referred to Tables 6.2 and 6.3.
The coefficient of discharge \( (C_D) \) was calculated from the equation given by Rouse (14).

\[
C_D = C_c \left[ \frac{1}{1 + C_c \cdot G/h} \right]^{\frac{1}{2}} \tag{6.1}
\]

where

- \( h \) is the depth of water infinitely far upstream.
- \( C_c \) was calculated by using energy method and momentum method in the finite element method.
- \( G \) is the gate opening.

All the computed values of \( C_D \) are shown in Fig. 6.19, Fig. 6.20, and Fig. 6.21 and also referred to Tables 6.2 and 6.3.
6.3 Contour Maps

The summation of squares of energy deviations along the downstream surface elements for each pair of \((A_0, B_0)\) was plotted on a graph of \(A_0\) vs \(B\) and a contour map was drawn for many pairs of \((A_0, B_0)\). From the closed contour map, a pair of \((A_0, B_0)\) corresponding to the minimum summation of squares of energy deviations was obtained.

The contour maps for the various types of gates and various upstream heads are shown in Fig. 6.1 to Fig. 6.18.

6.4 Downstream Free Surface Profile

The calculation of downstream free surface profile was based on the pair of \((A_0, B_0)\) which gave the minimum error in the finite element method.

All the graphs of downstream free surface profiles are shown in Fig. 6.10, Fig. 6.11 and Fig. 6.12.
### Table 6.2

**Computed $c_c$ and $c_d$ by Energy Method**

<table>
<thead>
<tr>
<th>No. of run</th>
<th>$\theta$</th>
<th>Total No. of elements</th>
<th>Total No. of unknown nodes (IN)</th>
<th>U/S head</th>
<th>$\omega$</th>
<th>No. of iteration</th>
<th>No. of D/S surface elements</th>
<th>$\epsilon^2$</th>
<th>$A_0$</th>
<th>$B_0$</th>
<th>$c_c$</th>
<th>$c_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°</td>
<td>61</td>
<td>18</td>
<td>24.0</td>
<td>1.2</td>
<td>13</td>
<td>6</td>
<td>6.400</td>
<td>3.117</td>
<td>1.170</td>
<td>0.610</td>
<td>0.58</td>
</tr>
<tr>
<td>2</td>
<td>0°</td>
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<td>18</td>
<td>15.0</td>
<td>1.2</td>
<td>13</td>
<td>6</td>
<td>3.100</td>
<td>3.130</td>
<td>1.200</td>
<td>0.600</td>
<td>0.58</td>
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<tr>
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<td>61</td>
<td>18</td>
<td>7.5</td>
<td>1.2</td>
<td>13</td>
<td>6</td>
<td>0.189</td>
<td>3.130</td>
<td>1.197</td>
<td>0.601</td>
<td>0.58</td>
</tr>
<tr>
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<td>15°</td>
<td>93</td>
<td>28</td>
<td>24.0</td>
<td>1.2</td>
<td>16</td>
<td>10</td>
<td>8.900</td>
<td>4.520</td>
<td>1.075</td>
<td>0.664</td>
<td>0.66</td>
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<tr>
<td>5</td>
<td>15°</td>
<td>93</td>
<td>28</td>
<td>15.0</td>
<td>1.2</td>
<td>15</td>
<td>10</td>
<td>4.000</td>
<td>4.220</td>
<td>1.180</td>
<td>0.636</td>
<td>0.63</td>
</tr>
<tr>
<td>6</td>
<td>15°</td>
<td>91</td>
<td>28</td>
<td>7.5</td>
<td>1.2</td>
<td>15</td>
<td>10</td>
<td>0.680</td>
<td>4.120</td>
<td>1.360</td>
<td>0.587</td>
<td>0.58</td>
</tr>
<tr>
<td>7</td>
<td>30°</td>
<td>93</td>
<td>28</td>
<td>24.0</td>
<td>1.2</td>
<td>15</td>
<td>10</td>
<td>6.500</td>
<td>4.300</td>
<td>1.150</td>
<td>0.676</td>
<td>0.69</td>
</tr>
<tr>
<td>8</td>
<td>30°</td>
<td>93</td>
<td>28</td>
<td>15.0</td>
<td>1.2</td>
<td>14</td>
<td>10</td>
<td>3.200</td>
<td>4.496</td>
<td>1.136</td>
<td>0.679</td>
<td>0.69</td>
</tr>
<tr>
<td>9</td>
<td>30°</td>
<td>93</td>
<td>28</td>
<td>7.5</td>
<td>1.2</td>
<td>16</td>
<td>10</td>
<td>0.530</td>
<td>4.570</td>
<td>1.210</td>
<td>0.658</td>
<td>0.58</td>
</tr>
<tr>
<td>No. of run</td>
<td>θ</td>
<td>Total No. of elements</td>
<td>Total No. of unknown nodes</td>
<td>U/S (IN)</td>
<td>ω</td>
<td>No. of iteration</td>
<td>No. of D/S surface elements</td>
<td>$c^2$</td>
<td>A₀</td>
<td>B₀</td>
<td>C₀</td>
<td>Cₜ</td>
</tr>
<tr>
<td>-----------</td>
<td>-----</td>
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<td>----------------------------</td>
<td>---------</td>
<td>-----</td>
<td>-----------------</td>
<td>----------------------------</td>
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<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
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<td>0°</td>
<td>133</td>
<td>42</td>
<td>24.0</td>
<td>1.1</td>
<td>48</td>
<td>10</td>
<td>4.27</td>
<td>3.650</td>
<td>1.145</td>
<td>0.618</td>
<td>0.57</td>
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<td>15.0</td>
<td>1.2</td>
<td>40</td>
<td>10</td>
<td>1.41</td>
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<td>1.186</td>
<td>0.605</td>
<td>0.57</td>
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<td>34</td>
<td>7.5</td>
<td>1.2</td>
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<td>15°</td>
<td>103</td>
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<td>1.2</td>
<td>22</td>
<td>10</td>
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<td>1.149</td>
<td>0.645</td>
<td>0.60</td>
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<td>15.0</td>
<td>1.2</td>
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<td>10</td>
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<td>3.875</td>
<td>1.193</td>
<td>0.635</td>
<td>0.59</td>
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<td>15°</td>
<td>91</td>
<td>28</td>
<td>7.5</td>
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<td>10</td>
<td>0.41</td>
<td>4.310</td>
<td>1.175</td>
<td>0.632</td>
<td>0.59</td>
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<td>1.2</td>
<td>44</td>
<td>10</td>
<td>0.73</td>
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<td>103</td>
<td>32</td>
<td>15.0</td>
<td>1.2</td>
<td>27</td>
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<td>0.55</td>
<td>3.350</td>
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<td>30°</td>
<td>97</td>
<td>30</td>
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<td>25</td>
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<td>4.860</td>
<td>1.152</td>
<td>0.671</td>
<td>0.59</td>
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</tbody>
</table>

Notes: When 1.7 or more was used for omega, the number of iteration was over 500. After 1.0, 1.1, 1.2, 1.3, 1.4 were tried for omega, it was found that the number of iteration was minimum when $\omega = 1.2$. 

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FIG. 6.1 CONTOUR MAP OF 24" UPSTREAM HEAD FOR SHARP EDGED GATE BY ENERGY PRINCIPLE

FIG. 6.2 CONTOUR MAP OF 15" UPSTREAM HEAD FOR SHARP EDGED GATE BY ENERGY PRINCIPLE
FIG. 6.3 CONTOUR MAP OF 7.5" UPSTREAM HEAD FOR SHARP EDGED GATE BY ENERGY PRINCIPLE

FIG. 6.4 CONTOUR MAP OF 24" UPSTREAM HEAD FOR 15° ANGLE GATE BY ENERGY PRINCIPLE
FIG. 6.5 CONTOUR MAP OF 15" UPSTREAM HEAD FOR 15° ANGLE GATE BY ENERGY PRINCIPLE

FIG. 6.6 CONTOUR MAP OF 7.5" UPSTREAM HEAD FOR 15° ANGLE GATE BY ENERGY PRINCIPLE

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Fig. 6.7 Contour map of 24" upstream head for 30° angle gate by energy principle.

Fig. 6.8 Contour map of 15" upstream head for 30° angle gate by energy principle.
FIG. 6.9 CONTOUR MAP OF 7.5" UPSTREAM HEAD FOR 30° ANGLE GATE BY ENERGY PRINCIPLE
FIG. 6.10 CONTOUR MAP OF 24" UPSTREAM HEAD FOR SHARP EDGED GATE BY MOMENTUM PRINCIPLE

FIG. 6.11 CONTOUR MAP OF 15" UPSTREAM HEAD FOR SHARP EDGED GATE BY MOMENTUM PRINCIPLE

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FIG. 6.12 CONTOUR MAP OF 7.5" UPSTREAM HEAD FOR SHARP EDGED GATE BY MOMENTUM PRINCIPLE

FIG. 6.13 CONTOUR MAP OF 24" UPSTREAM HEAD FOR 15° ANGLE GATE BY MOMENTUM PRINCIPLE
FIG. 6.16 CONTOUR MAP OF 24° UPSTREAM HEAD FOR 30° ANGLE GATE BY MOMENTUM PRINCIPLE

FIG. 6.17 CONTOUR MAP OF 15° UPSTREAM HEAD FOR 30° ANGLE GATE BY MOMENTUM PRINCIPLE
FIG. 6.18 CONTOUR MAP OF 7.5" UPSTREAM HEAD FOR 30° ANGLE GATE BY MOMENTUM PRINCIPLE

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FIG. 6.19 THEORETICAL COEFFICIENTS OF DISCHARGE FOR SHARP EDGED GATE
FIG. 6.20 THEORETICAL COEFFICIENTS OF DISCHARGE FOR 30° ANGLE GATE

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FIG. 6.21 THEORETICAL COEFFICIENTS OF DISCHARGE FOR 15° ANGLE GATE
CHAPTER 7

EXPERIMENTAL RESULTS

7.1 Downstream Free Surface Profile Measurement

At a number of stations on the downstream profile, the maximum and the minimum readings were taken, and an average check on the average reading was made by taking an estimated reading (by eye). If the check reading was not equal to the average of the maximum and the minimum readings, the three readings were averaged. This final average was subtracted from the reference reading, which was the reading of the gate lip, then this difference was subtracted from the gate opening, to get the depth of water at the section.

All the results of profile measurement are shown from Table 7.1 to Table 7.18 and also in Fig. 7.10, Fig. 7.11 and Fig. 7.12.

7.2 The Measurement of Coefficient of Contraction

At a downstream section, the water surface profile becomes nearly parallel and the depth of water almost equal to the tailwater depth. The maximum, the minimum and the check readings at this point were read and recorded then the depth of water was calculated. The ratio of this depth to the gate opening is known as the coefficient of contraction.
The experimental values of $C_c$ for different types of gates are shown in Fig. 7.1 to Fig. 7.9 and also referred to Table 7.19 to Table 7.27.

### 7.3 Coefficient of Discharge

The upstream head gate opening and the observed discharge were employed to calculate the $C_D$ by equation (7.1).

$$C_D = \frac{q}{G \sqrt{2gH}} \quad \text{...(7.1)}$$

where

$q = \text{discharge per unit width}$

$G = \text{gate opening}$

$H = \text{upstream head}$

All the results of $C_D$ are shown in Fig. 7.13 to Fig. 7.20 also referred to Table 7.19 to Table 7.26.
### EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE FOR SHARP EDGED GATE

Gate thickness = 0.47 ± 0.01 inches
Upstream head = 24.0 ± 0.125 inches
Gate opening = 3.016 ± 0.016 inches
Discharge = 1160 ± 10 U.S.G.P.M.
Reference reading = 23.47 ± 0.01 inches

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
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<td>22.945</td>
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<td>22.320</td>
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<td>22.24</td>
<td>22.31</td>
<td>22.312</td>
<td>1.858</td>
<td>0.0774</td>
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TABLE 7.2
EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR SHARP EDGED GATE

Gate thickness = 0.47 ± 0.01 inches
Upstream head = 15.0 ± 0.125 inches
Gate opening = 3.016 ± 0.016 inches
Discharge = 890 ± 10 U.S.G.P.M.
Reference reading = 23.47 ± 0.01 inches

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>X/H</th>
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<tbody>
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<td>0.0</td>
<td>0.0000</td>
<td>23.99</td>
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<td>22.34</td>
<td>22.34</td>
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<td>0.1257</td>
</tr>
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<td>22.34</td>
<td>1.886</td>
<td>0.1257</td>
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</table>

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TABLE 7.3

EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR SHARP EDGED GATE

Gate thickness = 0.47 ± 0.01 inches
Upstream head = 7.5 ± 0.125 inches
Gate opening = 3.016 ± 0.016 inches
Discharge = 600 ± 10 U.S.G.P.M.
Reference reading = 23.47 ± 0.01 inches

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
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</thead>
<tbody>
<tr>
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<td>0.3091</td>
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<td>0.2561</td>
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<td>0.6000</td>
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<td>22.22</td>
<td>22.38</td>
<td>22.375</td>
<td>1.921</td>
<td>0.2561</td>
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TABLE 7.4

EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR 15° BEVELLED GATE

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<thead>
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<th>Gate thickness</th>
<th>= 0.47 ± 0.01 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream head</td>
<td>= 24 ± 0.125 inches</td>
</tr>
<tr>
<td>Gate opening</td>
<td>= 3.0 ± 0.016 inches</td>
</tr>
<tr>
<td>Discharge</td>
<td>= 1200 ± 10 U.S.G.P.M.</td>
</tr>
<tr>
<td>Reference reading</td>
<td>= 23.49 ± 0.01 inches</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
</tr>
</thead>
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<td>22.99</td>
<td>23.02</td>
<td>23.017</td>
<td>2.527</td>
<td>0.105</td>
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<td>1.0</td>
<td>0.0417</td>
<td>22.86</td>
<td>22.77</td>
<td>22.81</td>
<td>22.812</td>
<td>2.322</td>
<td>0.096</td>
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<td>1.5</td>
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<td>22.58</td>
<td>22.65</td>
<td>22.652</td>
<td>2.162</td>
<td>0.090</td>
</tr>
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<td>0.0833</td>
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<td>22.49</td>
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<td>0.086</td>
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<td>0.1041</td>
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<td>22.42</td>
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<td>0.080</td>
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</tbody>
</table>

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TABLE 7.5

EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR 15° BEVELLED GATE

Gate thickness = 0.47 ± 0.01 inches
Upstream head = 15 ± 0.125 inches
Gate opening = 3.0 ± 0.016 inches
Discharge = 910 ± 10 U.S.G.P.M.
Reference reading = 23.49 ± 0.01 inches

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.0333</td>
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<td>22.95</td>
<td>22.99</td>
<td>22.990</td>
<td>2.500</td>
<td>0.166</td>
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<td>0.0667</td>
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<td>0.1667</td>
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TABLE 7.6

EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR 15° BEVELLED GATE

<table>
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<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
</tr>
</thead>
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<td>0.4000</td>
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<td>22.30</td>
<td>22.46</td>
<td>22.455</td>
<td>1.965</td>
<td>0.2620</td>
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</table>

Gate thickness = 0.47 ± 0.01 inches
Upstream head = 7.5 ± 0.125 inches
Gate opening = 3.0 ± 0.016 inches
Discharge = 610 ± 10 U.S.G.P.M.
Reference reading = 23.49 ± 0.01 inches

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**TABLE 7.7**

EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR 30° BEVELLED GATE

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
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<td>22.55</td>
<td>22.545</td>
<td>2.061</td>
<td>0.085</td>
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</table>

Gate thickness = 0.47 ± 0.01 inches
Upstream head = 24 ± 0.125 inches
Gate opening = 3.016 ± 0.016 inches
Discharge = 1250 ± 10 U.S.G.P.M.
Reference reading = 23.50 ± 0.01 inches

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TABLE 7.8

EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR 30° BEVELLED GATE

Gate thickness = 0.47 ± 0.01 inches
Upstream head = 15 ± 0.125 inches
Gate opening = 3.016 ± 0.016 inches
Discharge = 980 ± 10 U.S.G.P.M.
Reference reading = 23.50 ± 0.01 inches

<table>
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<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
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<td>2.666</td>
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<td>22.57</td>
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<td>22.41</td>
<td>22.54</td>
<td>22.535</td>
<td>2.051</td>
<td>0.136</td>
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</tbody>
</table>

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**EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE**

**FOR 30° BEVELLED GATE**

- **Gate thickness** = $0.47 \pm 0.01$ inches
- **Upstream head** = $3.016 \pm 0.016$ inches
- **Gate opening** = $7.5 \pm 0.125$ inches
- **Discharge** = $650 \pm 10$ U.S.G.P.M.
- **Reference reading** = $23.50 \pm 0.01$ inches

<table>
<thead>
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<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Min. Estimated</th>
<th>Final</th>
<th>Depth (in.)</th>
<th>Y/H</th>
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<tbody>
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<td>Max. Reading (in.)</td>
<td>Min. Reading (in.)</td>
<td>Estimated Reading (in.)</td>
<td>Final Reading (in.)</td>
</tr>
<tr>
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<td></td>
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<td>±0.01</td>
<td>±0.01</td>
<td>±0.01</td>
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**TABLE 7.10**

**EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE**

**FOR 15° BEVELLED GATE**

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.)</th>
<th>X/H</th>
<th>Max. Reading (in.)</th>
<th>Min. Reading (in.)</th>
<th>Estimated Reading (in.)</th>
<th>Final Reading (in.)</th>
<th>Depth (in.)</th>
<th>X/H</th>
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<td>22.527</td>
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<td>22.45</td>
<td>22.50</td>
<td>22.495</td>
<td>1.983</td>
<td>0.082</td>
</tr>
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<td>0.1875</td>
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<td>22.45</td>
<td>22.50</td>
<td>22.495</td>
<td>1.983</td>
<td>0.082</td>
</tr>
</tbody>
</table>

Gate thickness = 2.0 \(\pm\) 0.01 inches

Upstream head = 24 \(\pm\) 0.125 inches

Gate opening = 3.008 \(\pm\) 0.016 inches

Discharge = 1210 \(\pm\) 10 U.S.G.P.M.

Reference reading = 23.52 \(\pm\) 0.01 inches

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### Table 7.11

**Experimental Downstream Free Surface Profile for 15° Bevelled Gate**

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
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</thead>
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<td>23.01</td>
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<td>22.48</td>
<td>1.970</td>
<td>0.131</td>
</tr>
<tr>
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<td>0.3000</td>
<td>22.54</td>
<td>22.43</td>
<td>22.48</td>
<td>22.48</td>
<td>1.970</td>
<td>0.131</td>
</tr>
</tbody>
</table>

Gate thickness = 2.0 ± 0.01 inches

Upstream head = 15 ± 0.125 inches

Gate opening = 3.008 ± 0.016 inches

Discharge = 930 ± 10 U.S.G.P.M.

Reference reading = 23.52 ± 0.01 inches
# Table 7.12

**Experimental Downstream Free Surface Profile**

*For 15° Bevelled Gate*

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ± 0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ± 0.01</th>
<th>Min. Reading (in.) ± 0.01</th>
<th>Estimated Reading (in.) ± 0.01</th>
<th>Final Reading (in.) ± 0.005</th>
<th>Depth (in.) ± 0.005</th>
<th>X/H</th>
</tr>
</thead>
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<td>22.812</td>
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<td>22.505</td>
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<td>22.477</td>
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<td>22.48</td>
<td>22.477</td>
<td>1.965</td>
<td>0.262</td>
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</table>

Gate thickness = 2.0 ± 0.01 inches

Upstream head = 7.5 ± 0.125 inches

Gate opening = 3.008 ± 0.016 inches

Discharge = 600 ± 10 U.S.G.P.M.

Reference reading = 23.52 ± 0.01 inches

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**TABLE 7.13**

**EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE**

FOR 30° BEVELLED GATE

<table>
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<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
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<td>22.59</td>
<td>22.592</td>
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Gate thickness = 2.0 ± 0.01 inches
Upstream head = 24 ± 0.125 inches
Gate opening = 3.016 ± 0.016 inches
Discharge = 1290 ± 10 U.S.G.P.M.
Reference reading = 23.50 ± 0.01 inches

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TABLE 7.14

EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR 30° BEVELLED GATE

Gate thickness = 2.0 ± 0.01 inches
Upstream head = 15 ± 0.125 inches
Gate opening = 3.016 ± 0.016 inches
Discharge = 1000 ± 10 U.S.G.P.M.
Reference reading = 23.50 ± 0.01 inches

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<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) Y/H</th>
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<td>22.705</td>
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<td>22.65</td>
<td>22.655</td>
<td>2.171 ± 0.1447</td>
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<td>22.55</td>
<td>22.61</td>
<td>22.612</td>
<td>2.128 ± 0.1415</td>
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<td>0.2333</td>
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<td>22.51</td>
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<td>2.098 ± 0.1395</td>
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<td>0.2667</td>
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<td>22.560</td>
<td>2.076 ± 0.1381</td>
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</table>

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EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR 30° BEVELLED GATE

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
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</thead>
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<td>22.50</td>
<td>22.60</td>
<td>22.597</td>
<td>2.113</td>
<td>0.2817</td>
</tr>
</tbody>
</table>
## Table 7.16

**Experimental Downstream Free Surface Profile**

For 45° Bevelled Gate

- **Gate thickness** = 2.0 ± 0.01 inches
- **Upstream head** = 24 ± 0.125 inches
- **Gate opening** = 3.023 ± 0.016 inches
- **Discharge** = 1380 ± 10 U.S.G.P.M.
- **Reference reading** = 23.50 ± 0.01 inches

<table>
<thead>
<tr>
<th>Distance D/S from outer gate face (in.) ±0.01</th>
<th>X/H</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>Y/H</th>
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</thead>
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<td>0.5</td>
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<td>23.072</td>
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**TABLE 7.17**

**EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE**

**FOR 45° BEVELLED GATE**

- **Gate thickness** = 2.0 ± 0.01 inches
- **Upstream head** = 15 ± 0.125 inches
- **Gate opening** = 3.023 ± 0.016 inches
- **Discharge** = 1090 ± 10 U.S.G.P.M.
- **Reference reading** = 23.50 ± 0.01 inches

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<th>Distance D/S from outer gate face (in.) ±0.01</th>
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<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
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**TABLE 7.18**

EXPERIMENTAL DOWNSTREAM FREE SURFACE PROFILE
FOR 45° BEVELLED GATE

Gate thickness = 2.0 ± 0.01 inches
Upstream head = 7.5 ± 0.125 inches
Gate opening = 3.023 ± 0.016 inches
Discharge = 690 ± 10 U.S.G.P.M.
Reference reading = 23.50 ± 0.01 inches

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<th>Distance D/S from outer gate face (in.) ±0.01</th>
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<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
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### Experimental Cc and Cd for Sharp Edged Gate

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<th>U/S head (in.)</th>
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<th>Min. Reading (in.)</th>
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<th>Final Reading (in.)</th>
<th>Depth (in.)</th>
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Gate thickness = 0.47 ± 0.01 inches
Distance downstream from outer gate face = 4.50 ± 0.01 inches
Reference reading = 23.47 ± 0.01 inches
Gate opening = 3.016 ± 0.016 inches

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TABLE 7.20

EXPERIMENTAL $C_c$ AND $C_d$ FOR 30° BEVELLED GATE

Gate thickness = 0.47 ± 0.01 inches
Distance downstream from outer gate face = 4.5 ± 0.01 inches
Reference reading = 23.50 ± 0.01 inches
Gate opening = 3.016 ± 0.016 inches

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<th>Min. Reading (in.)</th>
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<th>Min. Reading (in.)</th>
<th>Estimated Reading (in.)</th>
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Gate thickness = 0.47 ± 0.01 inches
Distance downstream from outer gate face = 4.5 ± 0.01 inches
Reference reading = 23.49 ± 0.01 inches
Gate opening = 3.0 ± 0.016 inches

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### TABLE 7.22

**EXPERIMENTAL $C_c$ AND $C_d$ FOR 30° BEVELLED GATE**

Gate thickness $= 2.0 \pm 0.01$ inches

Distance downstream from outer gate face $= 4.5 \pm 0.01$ inches

Reference reading $= 23.50 \pm 0.01$ inches

Gate opening $= 3.016 \pm 0.016$ inches

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<th>U/S head (in.)</th>
<th>Discharge USGPM</th>
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<th>Min. Reading (in.)</th>
<th>Estimated Reading (in.)</th>
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TABLE 7.23

EXPERIMENTAL $C_c$ AND $C_d$ FOR 15° BEVELLED GATE

Gate thickness \( = 2.0 \pm 0.01 \) inches
Distance downstream from outer gate face = 4.50 ± 0.01 inches
Reference reading = 23.52 ± 0.01 inches
Gate opening = 3.008 ± 0.016 inches

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<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
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<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.00</td>
<td>1210</td>
<td>22.56</td>
<td>22.42</td>
<td>22.50</td>
<td>22.495</td>
<td>1.983</td>
<td>0.659</td>
<td>0.633</td>
</tr>
<tr>
<td>2</td>
<td>15.00</td>
<td>930</td>
<td>22.54</td>
<td>22.41</td>
<td>22.48</td>
<td>22.477</td>
<td>1.965</td>
<td>0.653</td>
<td>0.616</td>
</tr>
<tr>
<td>3</td>
<td>10.00</td>
<td>750</td>
<td>22.57</td>
<td>22.40</td>
<td>22.49</td>
<td>22.487</td>
<td>1.975</td>
<td>0.656</td>
<td>0.609</td>
</tr>
<tr>
<td>4</td>
<td>8.00</td>
<td>640</td>
<td>22.58</td>
<td>22.39</td>
<td>22.49</td>
<td>22.487</td>
<td>1.975</td>
<td>0.656</td>
<td>0.580</td>
</tr>
<tr>
<td>5</td>
<td>7.25</td>
<td>590</td>
<td>22.58</td>
<td>22.40</td>
<td>22.49</td>
<td>22.490</td>
<td>1.978</td>
<td>0.657</td>
<td>0.563</td>
</tr>
<tr>
<td>6</td>
<td>6.50</td>
<td>550</td>
<td>22.58</td>
<td>22.39</td>
<td>22.49</td>
<td>22.487</td>
<td>1.975</td>
<td>0.656</td>
<td>0.553</td>
</tr>
<tr>
<td>7</td>
<td>5.50</td>
<td>500</td>
<td>22.58</td>
<td>22.39</td>
<td>22.48</td>
<td>22.482</td>
<td>1.975</td>
<td>0.656</td>
<td>0.547</td>
</tr>
</tbody>
</table>

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### Table 7.24

**Experimental \( C_c \) and \( C_d \) for 45° Bevelled Gate**

<table>
<thead>
<tr>
<th>No. of Test</th>
<th>U/S head (in.) ±0.125</th>
<th>Discharge USGPM ±10</th>
<th>Max. Reading (in.) ±0.01</th>
<th>Min. Reading (in.) ±0.01</th>
<th>Estimated Reading (in.) ±0.01</th>
<th>Final Reading (in.) ±0.005</th>
<th>Depth (in.) ±0.005</th>
<th>( C_c )</th>
<th>( C_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.0</td>
<td>1380</td>
<td>22.86</td>
<td>22.72</td>
<td>22.78</td>
<td>22.785</td>
<td>2.308</td>
<td>0.763</td>
<td>0.72</td>
</tr>
<tr>
<td>2</td>
<td>15.0</td>
<td>1090</td>
<td>22.84</td>
<td>22.70</td>
<td>22.77</td>
<td>22.770</td>
<td>2.293</td>
<td>0.758</td>
<td>0.72</td>
</tr>
<tr>
<td>3</td>
<td>10.0</td>
<td>870</td>
<td>22.88</td>
<td>22.64</td>
<td>22.75</td>
<td>22.755</td>
<td>2.278</td>
<td>0.753</td>
<td>0.70</td>
</tr>
<tr>
<td>4</td>
<td>7.5</td>
<td>690</td>
<td>22.89</td>
<td>22.63</td>
<td>22.77</td>
<td>22.765</td>
<td>2.288</td>
<td>0.756</td>
<td>0.64</td>
</tr>
<tr>
<td>5</td>
<td>6.5</td>
<td>610</td>
<td>22.89</td>
<td>22.64</td>
<td>22.77</td>
<td>22.767</td>
<td>2.290</td>
<td>0.757</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Gate thickness = 2.0 ± 0.01 inches

Distance downstream from outer gate face = 4.5 ± 0.01 inches

Reference reading = 23.50 ± 0.01 inches

Gate opening = 3.023 ± 0.016 inches

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**TABLE 7.25**

**EXPERIMENTAL $C_c$ AND $C_d$ FOR SHARP CRESTED GATE**

Gate thickness  
$= 0.47 \pm 0.01$ inches

Distance downstream from outer gate face  
$= 4.50 \pm 0.01$ inches

Reference reading  
$= 38.345 \pm 0.005$ inches

Gate opening  
$= 6.016 \pm 0.016$ inches

<table>
<thead>
<tr>
<th>No. of Test</th>
<th>U/S head (in.) $\pm 0.125$</th>
<th>Discharge USGPM $\pm 10$</th>
<th>Max. Reading (in.) $\pm 0.01$</th>
<th>Min. Reading (in.) $\pm 0.01$</th>
<th>Estimated Reading (in.) $\pm 0.005$</th>
<th>Final Reading (in.) $\pm 0.005$</th>
<th>Depth (in.) $\pm 0.005$</th>
<th>$C_c$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.50 2070</td>
<td>36.09</td>
<td>35.87</td>
<td>35.940</td>
<td>35.960</td>
<td>3.631</td>
<td>0.6035</td>
<td>0.568</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>20.50 2000</td>
<td>36.10</td>
<td>35.87</td>
<td>35.940</td>
<td>35.962</td>
<td>3.633</td>
<td>0.6038</td>
<td>0.565</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>20.00 1980</td>
<td>36.10</td>
<td>35.87</td>
<td>35.940</td>
<td>35.962</td>
<td>3.633</td>
<td>0.6038</td>
<td>0.566</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>19.00 1930</td>
<td>36.10</td>
<td>35.87</td>
<td>35.940</td>
<td>35.962</td>
<td>3.633</td>
<td>0.6038</td>
<td>0.565</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>17.75 1840</td>
<td>36.11</td>
<td>35.88</td>
<td>35.950</td>
<td>35.972</td>
<td>3.643</td>
<td>0.6055</td>
<td>0.555</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>17.00 1760</td>
<td>36.10</td>
<td>35.88</td>
<td>35.950</td>
<td>35.970</td>
<td>3.641</td>
<td>0.6052</td>
<td>0.542</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>15.00 1670</td>
<td>36.12</td>
<td>35.87</td>
<td>35.955</td>
<td>35.975</td>
<td>3.646</td>
<td>0.6060</td>
<td>0.552</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>12.50 1420</td>
<td>36.11</td>
<td>35.89</td>
<td>35.950</td>
<td>35.975</td>
<td>3.646</td>
<td>0.6060</td>
<td>0.508</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>12.00 1400</td>
<td>36.10</td>
<td>35.89</td>
<td>35.950</td>
<td>35.972</td>
<td>3.643</td>
<td>0.6055</td>
<td>0.517</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>11.00 1300</td>
<td>36.12</td>
<td>35.88</td>
<td>35.960</td>
<td>35.985</td>
<td>3.651</td>
<td>0.6068</td>
<td>0.500</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>10.00 1220</td>
<td>36.13</td>
<td>35.89</td>
<td>35.960</td>
<td>35.982</td>
<td>3.656</td>
<td>0.6070</td>
<td>0.494</td>
<td></td>
</tr>
</tbody>
</table>


TABLE 7.26

EXPERIMENTAL $C_c$ AND $C_d$ FOR SHARP EDGED GATE

Gate thickness $= 0.47 \pm 0.01$ inches

Distance downstream from outer gate face $= 4.50 \pm 0.01$ inches

Reference reading $= 33.37 \pm 0.01$ inches

Gate opening $= 1.023 \pm 0.016$ inches

<table>
<thead>
<tr>
<th>No. of Test</th>
<th>U/S head (in.)</th>
<th>Discharge USGPM</th>
<th>Max. Reading (in.)</th>
<th>Min. Reading (in.)</th>
<th>Estimated Reading (in.)</th>
<th>Final Reading (in.)</th>
<th>Depth (in.)</th>
<th>$C_c$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.000</td>
<td>370</td>
<td>33.015</td>
<td>32.990</td>
<td>33.005</td>
<td>33.004</td>
<td>0.657</td>
<td>0.642</td>
<td>0.623</td>
</tr>
<tr>
<td>2</td>
<td>13.350</td>
<td>300</td>
<td>33.020</td>
<td>32.985</td>
<td>33.000</td>
<td>33.001</td>
<td>0.654</td>
<td>0.639</td>
<td>0.620</td>
</tr>
<tr>
<td>3</td>
<td>7.750</td>
<td>220</td>
<td>33.035</td>
<td>32.980</td>
<td>33.000</td>
<td>33.004</td>
<td>0.657</td>
<td>0.642</td>
<td>0.595</td>
</tr>
<tr>
<td>4</td>
<td>4.500</td>
<td>170</td>
<td>33.035</td>
<td>32.980</td>
<td>33.005</td>
<td>33.006</td>
<td>0.659</td>
<td>0.644</td>
<td>0.601</td>
</tr>
<tr>
<td>5</td>
<td>3.000</td>
<td>130</td>
<td>33.055</td>
<td>32.990</td>
<td>33.020</td>
<td>33.021</td>
<td>0.674</td>
<td>0.659</td>
<td>0.561</td>
</tr>
<tr>
<td>6</td>
<td>2.125</td>
<td>110</td>
<td>33.090</td>
<td>33.020</td>
<td>33.050</td>
<td>33.052</td>
<td>0.705</td>
<td>0.689</td>
<td>0.565</td>
</tr>
</tbody>
</table>

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For \( t = 0.47 \) inches
\[ G = 6.016 \text{ inches} \]

**FIG. 7.1** EXPERIMENTAL COEFFICIENTS OF CONTRACTION FOR SHARP EDGED GATE

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For $t=0.47$ inches
$G=3.016$ inches

FIG. 7.2 EXPERIMENTAL COEFFICIENTS OF CONTRACTION FOR SHARP EDGED GATE

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For $t = 0.47$ inches
$G = 1.023$ inches

FIG. 7.3 EXPERIMENTAL COEFFICIENTS OF CONTRACTION FOR SHARP EDGED GATE

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For $t=0.47$ inches
$G=3.016$ inches

FIG. 7.4 EXPERIMENTAL COEFFICIENTS OF CONTRACTION FOR 30° ANGLE GATE
For $t=2.0$ inches, $G=3.016$ inches

For $t=0.47$ inches, $G=3.016$ inches

**FIG. 7.5 EXPERIMENTAL COEFFICIENTS OF CONTRACTION FOR 30° ANGLE GATE FOR DIFFERENT GATE THICKNESS**

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For $t=0.47$ inches
$G=3.0$ inches

**FIG. 7.6** EXPERIMENTAL COEFFICIENTS OF CONTRACTION OF SLUICE GATE FOR 15° ANGLE GATE
For $t = 2.0$ inches, $G = 3.008$ inches

For $t = 0.47$ inches, $G = 3.0$ inches

FIG. 7.7 COMPARISON OF EXPERIMENTAL COEFFICIENTS OF CONTRACTION OF DIFFERENT GATE THICKNESS FOR 15° ANGLE GATE

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For $t=0.47$ inches
$G=3.0$ inches

**FIG. 7.8 EXPERIMENTAL COEFFICIENTS OF CONTRACTION FOR 45° ANGLE GATE**

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FIG. 7.9 COMPARISON OF EXPERIMENTAL COEFFICIENTS OF CONTRACTION OF DIFFERENT GATE THICKNESS FOR 45° ANGLE GATE

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Theoretical Values:
- Momentum Principle And Finite Element Method
- Energy Principle And Finite Element Method

Experimental Values

FIG. 7.10 COMPARISON OF DOWNSTREAM SURFACE PROFILE FOR SHARP EDGED GATE
Theoretical Values:
- Momentum Principle And Finite Element Method
- Energy Principle And Finite Element Method

Experimental Values

FIG. 7.11 COMPARISON OF DOWNSTREAM SURFACE PROFILE FOR 15° ANGLE GATE

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Theoretical Values:
- Momentum Principle And Finite Element Method
- Energy Principle And Finite Element Method

Experimental Values

FIG. 7.12 COMPARISON OF DOWNSTREAM SURFACE PROFILE FOR 30° ANGLE GATE

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For $t = 0.47$ inches, $G = 3.016$ inches

**FIG. 7.13** EXPERIMENTAL COEFFICIENTS OF DISCHARGE FOR SHARP EDGED GATE

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
For $t=2.0$ inches, $G=3.016$ inches
For $t=0.47$ inches, $G=3.016$ inches

FIG. 7.14 EXPERIMENTAL COEFFICIENTS OF DISCHARGE FOR 30° ANGLE GATE WITH DIFFERENT THICKNESS
For \( t = 0.47 \) inches, \( G = 3.016 \) inches

FIG. 7.15 EXPERIMENTAL COEFFICIENTS OF DISCHARGE FOR 30° ANGLE GATE
For $t = 0.47$ inches
$G = 3.0$ inches

FIG. 7.16 EXPERIMENTAL COEFFICIENTS OF DISCHARGE FOR 15° ANGLE GATE
Fig. 7.17 Experimental coefficients of discharge for 15° angle gate with different thickness

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For $t=2.0$ inches
$G=3.016$ inches

FIG. 7.18 EXPERIMENTAL COEFFICIENTS OF DISCHARGE FOR 45° ANGLE GATE
For $t = 0.47$ inches
$G = 6.016$ inches

**FIG. 7.19** EXPERIMENTAL COEFFICIENTS OF DISCHARGE FOR SHARP EDGED GATE

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For \( t = 0.47 \) inches
\[ G = 1.023 \text{ inches} \]

**FIG. 7.20 EXPERIMENTAL COEFFICIENTS OF DISCHARGE FOR SHARP EDGED GATE**
CHAPTER 6

DISCUSSION

8.1 The Choice of Elements

In the finite element method, the degree of accuracy depends on how the elements are used. It is best for the shape of the triangle element to approach a right-angled triangle if possible. Within some limits, the greater the number of elements chosen, the better accuracy of the solution. However, this gives more unknown values due to more elements and thus the computation time increases.

a) In the theoretical work, the total energy head on all the downstream surface elements is desired. The total energy head equals the addition of velocity head, pressure head and elevation head. The pressure head and elevation head can be found from the flow pattern, but the velocity head should be developed from the slope matrix by using the finite element method. According to the basic assumption of this finite element analysis, the velocity is constant within each element. The calculated velocity head corresponds to the centroid of each element. By the principle of free vortex flow and the curvature of the downstream surface profile, this centroidal velocity head can be transposed to
the free surface. The surface elevation head is then added to the velocity head to get the total head.

b) Momentum principle was also employed to calculate the constant total energy head on all the downstream elements. The pressure head on the gate was found by subtracting the velocity head from the total head on the gate. The total force on the gate was obtained by integrating all the pressure heads along the gate. By Bernoulli's equation, the upstream velocity head was found first and the upstream free surface adjusted. Then through the momentum balance between upstream and downstream, the total energy line for all the downstream elements was estimated.

In order to obtain a good solution, it is necessary to have sufficient small triangle elements along upstream side of the gate and the downstream free surface. The numbers of elements along the upstream side of the gate used in the numerical work is shown in Table 8.1. The numbers of elements along the downstream free surface used in the numerical work are shown in Tables 6.2 and 6.3.

Table 8.1 No. of Elements along Upstream Side of the Gate

<table>
<thead>
<tr>
<th>Gate Angle</th>
<th>0°</th>
<th>15°</th>
<th>30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>U/S head (in.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td>10</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>15.0</td>
<td>8</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>7.5</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
8.2 Comparison of Energy Method and Momentum Method

In the energy method, it is assumed that there is no energy loss when the fluid flows through the sluice gate. Actually this is not exactly true. Generally speaking, there is a small energy loss of the order of \(0.1 \frac{v^2}{2g}\) in the sluice gate problem. In the momentum method, the balance of momentum of upstream and downstream was considered. It has nothing to do with the energy dissipated.

Table 8.2 and Fig. 8.3, Fig. 8.4, Fig. 8.6 show the percentage errors and comparing the energy method and momentum method with the experimental results. From this comparison, it is observed that the error by using energy method is higher than by using momentum method.

8.3 The Difference between Experimental and Computed Results

The difference between experimental and theoretical results can be explained by the existence of a boundary layer which has approximately zero thickness at the gate and increases in thickness downstream. The difference at low upstream head is higher than at high upstream head. The difference at high head can be explained by the existence of laminar boundary layer and the difference at low head can be explained by the existence of turbulent boundary layer.

For laminar boundary layer, the thickness \(\delta\) can be
obtained from:
\[
\frac{\delta}{x} = 5\left(\frac{V}{U}\right)^{-\frac{3}{2}}
\] 

...(8.1)

where

\[ U = \frac{\mu}{\rho} \] the kinematic viscosity
\[ V \] the free-stream velocity outside the boundary layer.

For turbulent boundary layer
\[
\frac{\delta}{x} = 0.38 \left(\frac{V}{U}\right) \frac{1}{5}
\] 

...(8.2)

For sharp crested gate, at the head of 24 inches, it was calculated that the laminar boundary layer thickness was 0.003 inches and at the head of 7.5 inches, we can find the turbulent boundary layer thickness to be 0.091 inches. Thus a boundary layer correction can help to bring the experimental results into agreement with the theory.

Henderson (16) relates the boundary layer thickness \( \delta \), to the gate opening \( G \) and Reynolds number. For laminar flow and for flows having similar Froude numbers, he shows that the discrepancies \( \Delta_i \), between experimental and theoretical values of \( C_\infty \) are related by:

\[
\frac{\Delta_1}{\Delta_2} = \left(\frac{G_2}{G_1}\right)^{3/4} = 2.25
\]

\[
\frac{\Delta_2}{\Delta_3} = \left(\frac{G_3}{G_2}\right)^{3/4} = 1.65
\]

\[
\frac{\Delta_1}{\Delta_3} = \left(\frac{G_3}{G_1}\right)^{3/4} = 3.72
\] 

...(8.3)
in which

\[
\Delta_1 = \text{the discrepancy in } C_c \text{ for } G_1 = 1.023 \text{ inches}, \\
\Delta_2 = \text{the discrepancy in } C_c \text{ for } G_2 = 3.016 \text{ inches}, \\
\Delta_3 = \text{the discrepancy in } C_c \text{ for } G_3 = 6.016 \text{ inches},
\]

where

\[G_1, G_2, G_3 \text{ are the gate openings for sharp edged gates.}\]

The values in Fig. 8.1 show good confirmation of this equation for low head.

### 8.4 Comparison of Different Theoretical Solutions

The coefficients of contraction curves for sharp edged gate obtained by Southwell and Vaisey (4), Pajer (3), Perry (6), Benjamin (5), Fangmeier and Strelkoff(7), Larock (11) are shown in Fig. 8.2 and Fig. 8.5. These curves are compared with the computed points obtained by using the finite element method, the correlation is quite good for the energy and momentum method except for high head under momentum principle. This slight difference for high head probably results from underestimating the force of the gate on the flow due to insufficient number of elements along the gate.

### 8.5 Contour Map

In the contour maps of the summation of squares of energy
deviations (Fig. 6.1 to Fig. 6.18), the inner closed contour is long and narrow when the energy principle is used and it is not easy to obtain the correct $A_0$ and $B_0$ from the map. The inner closed contour obtained by using the momentum principle is more circular, and the variation between the extreme ends is not large, thus one can find the answer from this map more easily. Thus the error in $A_0$, $B_0$ by using energy principle could be larger than that by using momentum principle.

For the vertical sharp crested gate, the coefficient of contraction depends on the parameter $B_0$ only. The symmetrical centre lines of the closed contour lines are nearly horizontal and vertical. For the angle gate, the coefficient of contraction depends on both $A_0$ and $B_0$. The lines of symmetry of the closed contour are inclined.

8.6 The Accuracy of Experimental Readings

The approximate errors from different sources are indicated as follows:

(A) Sources of errors

a) The errors that might occur in the measurement of flow rate are as follows:

1) Minor leakage from the leaks between gate and flume walls.
2) Magnetic flow meter reading.
3) Magnetic flow meter calibration.
4) Baffle disturbance.
5) Air entrainment.

b) Errors that might occur in experimental determination of $C_c$ and $C_d$ for various gate openings are:

1) The large fluctuations at downstream water surface at low upstream head for 6.016 inches gate opening.
2) The small fluctuations at downstream water surface at low upstream head for 3.016 inches gate opening.
3) Almost no fluctuation at downstream water surface for 1.023 inches gate opening.
4) Errors that occurred in electric point gauge reading.
5) Errors that occurred in scale reading.
6) Errors in measured discharge.

(B) Approximate values of the error in reading the readings are:

a) Magnetic flow meter reading

1) Zero reading 20 U.S.G.P.M
2) Calibration reading ±5 U.S.G.P.M
3) Discharge reading ±10 U.S.G.P.M

b) Upstream water level fluctuation

1) For high head for 3. IN. gate opening ±0.25 IN.
2) For low head for 3. IN. gate opening ±0.5 IN.
3) For high head for 6. IN. gate opening ±0.25 IN.
4) For low head for 6. IN. gate opening ±0.5 IN.
5) For high head for 1. IN. gate opening ±0.125 IN.
6) For low head for 1. IN. gate opening ±0.25 IN.

c) Electric point gauge reading
1) Calibration reading ±0.005 IN.
2) Downstream water level reading ±0.01 IN.
3) Downstream zero reading ±0.01 IN.

d) Scale reading
1) Gate opening reading ±0.016 IN.
2) Horizontal distance downstream from the gate ±0.125 IN.
3) Upstream water level scale reading ±0.125 IN.

8.7 The Accuracy of Results

(a) The scatter of experimental results

The experimental results of coefficient of contraction in Fig. 7.1 to Fig. 7.8 are scatter to some extent. The summations of the squares of residuals from the average curve are shown below in Table 8.3 for different types of gates. These residuals are the deviations of all experimental points from the average curve, and are measured in the direction of vertical axis.

The value of $\epsilon^2/n$ indicates the extent of the scatter of the experimental reading. This scatter condition is very little for the gates of increased thickness. These extended gate lips result in smooth and stable downstream

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water surfaces.

The scatter of experimental results and the apparent scale effects could be explained partly due to the reading errors given in section 8.6.

(b) The percentage error of $C_D$

The experimental coefficient of discharge was based on the measured discharge, which is expressed by the equation 7.1. The maximum coefficient of discharge can be obtained by equation 8.4.

$$\text{Max. } C_D = C_c \sqrt{\frac{D - G \cdot C_c}{D}} \quad \ldots(8.4)$$

where

$C_c$ is the experimental coefficient of contraction.

$G$ is the gate opening.

$D$ is the upstream head.

and the percentage error of $C_D$ can be found from the equation 8.5

$$P_e = \frac{\text{Max. } C_D - C_m}{\text{Max. } C_D} \times 100 \quad \ldots(8.5)$$

where

$P_e$ is the percentage error of $C_D$.

$C_D$ is the experimental coefficient of discharge in Table 7.19 to Table 7.26.

Max. $C_D$ is the maximum coefficient of discharge by equation 8.4.
The percentage errors of $C_D$ calculated from equation 8.5 are shown in Fig. 8.7. It is found that the average percentage error of $C_D$ for this experimental study is -2.0%.

(c) Some limits on the readings

Since the flume used for the experimental work is three feet high, the experimental results for very high upstream heads could not be obtained. For very low heads, serious fluctuations occurred at downstream side. No reading could be obtained when the head was below a certain level. The upper and lower limits of reading are shown in the graphs (Fig. 7.1 to Fig. 7.8).

When the gate lip angle $\theta$ increases and reaches to some limiting value, the water detaches from the lip of the gate and the gate performs like "vertical sharp crested gate" except $C$ is increased. No reading for $45^\circ$ angle gate with 0.47 inches thickness could be obtained when the upstream head was higher than 6 inches.
### TABLE 8.2

**TABLE OF PERCENTAGE ERROR OF $C_c$.**

<table>
<thead>
<tr>
<th>Gate angle $\theta$</th>
<th>U/S head (IN)</th>
<th>$A_0$</th>
<th>$B_0$</th>
<th>$C_c$</th>
<th>%age error</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Method</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>24.0</td>
<td>3.117</td>
<td>1.170</td>
<td>0.610</td>
<td>0.32 %</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>15.0</td>
<td>3.130</td>
<td>1.200</td>
<td>0.600</td>
<td>1.33 %</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>7.5</td>
<td>3.130</td>
<td>1.197</td>
<td>0.601</td>
<td>4.00 %</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>24.0</td>
<td>4.520</td>
<td>1.075</td>
<td>0.664</td>
<td>1.40 %</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>15.0</td>
<td>4.220</td>
<td>1.180</td>
<td>0.636</td>
<td>1.40 %</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>7.5</td>
<td>4.120</td>
<td>1.360</td>
<td>0.587</td>
<td>1.20 %</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>24.0</td>
<td>4.300</td>
<td>1.150</td>
<td>0.676</td>
<td>2.00 %</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>15.0</td>
<td>4.496</td>
<td>1.136</td>
<td>0.679</td>
<td>1.70 %</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>7.5</td>
<td>4.570</td>
<td>1.210</td>
<td>0.658</td>
<td>5.90 %</td>
</tr>
<tr>
<td><strong>Momentum Method</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>24.0</td>
<td>3.650</td>
<td>1.145</td>
<td>0.618</td>
<td>1.45 %</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>15.0</td>
<td>3.390</td>
<td>1.186</td>
<td>0.605</td>
<td>0.50 %</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>7.5</td>
<td>4.115</td>
<td>1.194</td>
<td>0.602</td>
<td>3.82 %</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>24.0</td>
<td>4.220</td>
<td>1.149</td>
<td>0.645</td>
<td>3.80 %</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>15.0</td>
<td>3.875</td>
<td>1.193</td>
<td>0.635</td>
<td>1.50 %</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>7.5</td>
<td>4.310</td>
<td>1.175</td>
<td>0.632</td>
<td>5.00 %</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>24.0</td>
<td>3.020</td>
<td>1.177</td>
<td>0.694</td>
<td>0.14 %</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>15.0</td>
<td>3.350</td>
<td>1.220</td>
<td>0.677</td>
<td>1.33 %</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>7.5</td>
<td>4.860</td>
<td>1.152</td>
<td>0.671</td>
<td>3.80 %</td>
</tr>
</tbody>
</table>

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## TABLE 8.3
THE SCATTER OF EXPERIMENTAL RESULTS

<table>
<thead>
<tr>
<th>Gate angle</th>
<th>Gate opening (IN)</th>
<th>Gate thickness (IN)</th>
<th>$\sum \epsilon^2$ ($C_\text{unit})^2$</th>
<th>No. of reading pt. (n)</th>
<th>$\sum \epsilon^2/n$ ($C_\text{unit})^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1.023</td>
<td>0.47</td>
<td>0.848x10^{-3}</td>
<td>14</td>
<td>0.606x10^{-4}</td>
</tr>
<tr>
<td>0°</td>
<td>3.016</td>
<td>0.47</td>
<td>1.326x10^{-3}</td>
<td>29</td>
<td>0.457x10^{-4}</td>
</tr>
<tr>
<td>0°</td>
<td>6.016</td>
<td>0.47</td>
<td>Almost zero</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>15°</td>
<td>3.000</td>
<td>0.47</td>
<td>3.735x10^{-6}</td>
<td>60</td>
<td>0.623x10^{-4}</td>
</tr>
<tr>
<td>30°</td>
<td>3.016</td>
<td>0.47</td>
<td>1.133x10^{-3}</td>
<td>40</td>
<td>0.283x10^{-4}</td>
</tr>
<tr>
<td>15°</td>
<td>3.008</td>
<td>2.00</td>
<td>0.080x10^{-3}</td>
<td>28</td>
<td>0.029x10^{-4}</td>
</tr>
<tr>
<td>30°</td>
<td>3.016</td>
<td>2.00</td>
<td>0.900x10^{-3}</td>
<td>32</td>
<td>0.281x10^{-4}</td>
</tr>
<tr>
<td>45°</td>
<td>3.023</td>
<td>2.00</td>
<td>0.083x10^{-3}</td>
<td>20</td>
<td>0.042x10^{-4}</td>
</tr>
</tbody>
</table>
Theoretical Results By Finite Element Method
- By Momentum Principle
- By Energy Principle

Experimental Results
- For t = 0.47 inches

Experimental Results By Benjamin(5)
- 1.02 inches Gate Opening
- 3.57 inches Gate Opening

FIG. 8.1 COEFFICIENTS OF CONTRACTION FOR SHARP EDGED GATE FOR DIFFERENT GATE OPENING
Theoretical Values

- Perry (6)
- Pajer (3)
- Fangmeier & Strelkoff (7)
- Southwell & Vaisey (4)
- Benjamin (5)
- Larock (11)

- Momentum Principle & Finite Element Method
- Energy Principle & Finite Element Method

FIG. 8.2 THEORETICAL COEFFICIENTS OF CONTRACTION FOR SHARP EDGED GATE BY DIFFERENT METHODS

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Theoretical Values
- Momentum Principle And Finite Element Method
- Energy Principle And Finite Element Method

Experimental Values
--- For \( t=0.47 \) inches and \( G=3.016 \) inches

**FIG. 8.3 COMPARISON OF EXPERIMENTAL RESULTS WITH THEORETICAL RESULTS FOR SHARP EDGED GATE**

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Theoretical Values
- Momentum Principle And Finite Element Method
- Energy Principle And Finite Element Method

Experimental Values
For t = 0.47 inches, G = 3.016 inches

**FIG. 8.4** COMPARISON OF EXPERIMENTAL COEFFICIENTS OF CONTRACTION WITH THEORETICAL COEFFICIENTS OF CONTRACTION FOR 30° ANGLE GATE

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Theoretical Values

- Momentum Principle And Finite Element Method
- Energy Principle And Finite Element Method
- Larock (11)

FIG. 8.5 COMPARISON OF THEORETICAL COEFFICIENTS OF CONTRACTION FOR 30° ANGLE GATE
Theoretical Values

- Momentum Principle And Finite Element Method
- Energy Principle And Finite Element Method

Experimental Values

For t = 0.47 inches, G = 3.0 inches

FIG. 8.6 COMPARISON OF EXPERIMENTAL RESULTS WITH THEORETICAL RESULTS FOR 15° ANGLE GATE

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FIG. 8.7 PERCENTAGE ERROR OF $C_D$
The Laplace equation for gravity flow under a sluice gate has been written in terms of an unknown stream function and an unknown distribution of free surface coordinates. The Laplace equation was solved by the finite element method through iterative, numerical steps to the desired degree of accuracy. The outflow free surface was approximated by an elliptical equation and the parameters $A_0$ and $B_0$ of the ellipse were found by either a contour map method or a finite difference method in the finite element programme.

The computed results for the vertical sharp crested gate compare satisfactorily with the results of other investigators except one result for 24 inches upstream head from the momentum method. This small difference was considered to be due to the inadequate number of elements chosen along the upstream inner gate face to calculate the force on the gate.

The computed results for $30^\circ$ bevelled gate compare satisfactorily with Larock's work in which he used a method of combining conformal mapping and a Riemann-Hilbert solution for an inclined planar gate of $30^\circ$ angle.

Since viscosity and surface tension were omitted from the finite element analysis (e.g. the growth of a boundary
layer on the flume bottom downstream of the gate. The experimental values of $C_c$ are generally larger than the theoretical values in the range of gate opening to total head ratios considered.

Each solution requires almost ten minutes of computer time.
REFERENCE

1- Rayleigh, Lord, Phil. Mag. (5) 2, f41; Collected Papers 1, 297, Cambridge University Press, 1876.


FLOW CHART FOR FINITE ELEMENT SOLUTION AND DOWNSTREAM FREE SURFACE CALCULATION

START

DIMENSIONS AND READING STATEMENTS

SET COORDINATES FOR DOWNSTREAM SURFACE BASED ON Ao, Bo, THETA

CALL SUBROUTINE ASA
MAKE CORRECTION FOR UPSTREAM FREE SURFACE

SET STREAM FUNCTION VALUES FOR ALL THE NODES

IE=1

STIFFNESS MATRIX

ASSEMBLE EQUATIONS A(IN,IT), W(IN)

SOLVE FOR PSI(IN)

CALL SUBROUTINE CISA
CALCULATE DOWNSTREAM TOTAL ENERGY HEAD

CALCULATE Σ ε² OF DOWNSTREAM SURFACE ELEMENTS

CHANGE Ao, Bo, BY FINITE DIFFERENCE METHOD
Ao_{n+1} = Ao_n + da, Bo_{n+1} = Bo_n + db

STOP
FLOW CHART FOR STIFFNESS MATRIX

1. ENTER
2. IE = 1
3. IR = I(IE), JR = J(IE), KR = K(IE)
4. B(IR) = Y(JR) - Y(KR)
5. C(IR) = X(KR) - X(JR)
6. B(JR) = Y(KR) - Y(IR)
7. C(JR) = X(IR) - X(KR)
8. B(KR) = Y(IR) - Y(JR)
9. C(KR) = X(JR) - X(IR)
10. CALCULATE AREA(IE)
11. MO = 1
12. IR = I(IE)
13. IS = I(IE)
14. IRT = 1
15. IST = 1
16. BBGCC(IRT, IST, IE) = (B(IR) B(IS) + C(IR) C(IS))/AREA(IE)
17. GO TO 101, 102, 103, 104, 105, 106, m0
18. IS = J(IE)
19. IST = 2
20. BBGCC(IST, IRT, IE) = BBGCC(IRT, IST, IE)
21. BBGCC(IST, IRT, IE) = BBGCC(IRT, IST, IE)
22. BBGCC(IST, IRT, IE) = BBGCC(IRT, IST, IE)
23. IE = IE + 1
24. IE = IE
25. IE = IE + 1
26. ASSEMBLE EQUATION A(IN, IT), W(IN)
FLOW CHART OF ASSEMBLE EQUATION

ENTER

$W(IN) = 0.0, A(IN, IR) = 0.0$

$IN = IN + 1$

$IE = 1$

$I(IE) - IN$

$J(IE) - IN$

$K(IE) - IN$

$IR = I(IE)$

$INT = 1$

$IRT = 1$

$JR = J(IE)$

$KR = K(IE)$

$M = 1$

$A(IN, IR) = A(IN, IR) + BBPCU(INT, IRT, IE)$

GO TO 141, 142, 143, $M$

\[ M = M + 1 \]

$IRT = IRT + 1$

$IE = IE + 1$

SOLVE FOR $PSI(IN)$

$W(IN) = W(IN) - BBPCU(INT, INT, IE)$

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FLOW CHART FOR SOLVING PSI(IN)

ENTER

ITER=1
BO(IN)=OMEGA/A(IN,IN)
BIT=1.0-OMEGA

ITER=ITER+1
D1=0.0
IN=1

EX=0.0
IT=1

W(IN)-0.0

IT-IN = IT-MA ≥

EX=W(IN)

A(IN,IT)-0.0

EX=EX-A(IN,IT) PSI(IT)

IT-MA ≥

IT=IT+1

A(IN,IT)-0.0

EX=BO(IN)xEX+BITxPSI(IN)

(PSI(IN)-EX)-D1

D1= PSI(IN)-EX

PSI(IN)=EX

IN-MA ≥ D1-EPS

PRINT PSI(IN)

CALCULATE \[ \Sigma \epsilon^2 \]

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FLOW CHART FOR $\sum \varepsilon^2$ CALCULATION

1. ENTER
2. CALL SUBROUTINE CISA
3. CALCULATE $E_0$
4. $E_P = 0.0$
5. DO 66 $i = 1, 10$
6. $M = (2 \cdot N) - 1$, $M = 2 \cdot i$
7. $IR = I(M)$, $JR = J(M)$, $KR = K(M)$
8. $B(IR) = Y(JR) - Y(KR)$, $C(IR) = X(KR) - X(JR)$
9. $B(JR) = Y(KR) - Y(IR)$, $C(JR) = X(IR) - X(KR)$
10. $B(KR) = Y(IR) - Y(JR)$, $C(KR) = X(JR) - X(IR)$
11. CALCULATE $V_X(M)$, $V_Y(M)$, $V_H(M)$
12. CORRECT VELOCITY HEAD
   $V_{HH}(M) = V_H(M)[(1 + \Delta/\rho)^2]$}
13. CALCULATE $Y_M(M)$
14. $E_BI(M) = V_{HH}(M) + Y_H(M)$
15. $E_FC(M) = E_0 - E_BI(M)$
16. $E_P = \sum (E_FC)^2$
17. PRINT $E_P$
18. CHANGE $A_0$, $B_0$
   $A_{n+1} = A_n + da$, $B_{n+1} = B_n + db$

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FLOW CHART OF SUBROUTINE ASA

\[
R1 = -\frac{2gQ}{2} + \frac{2gQ^2}{4} - \frac{V^2 + 2gQCC}{27}^3
\]

\[
R2 = -\frac{2gQ}{2} + \frac{2gQ^2}{4} - \frac{V^2 + 2gQCC}{27}^3
\]

\[
RT1 = R1
\]
\[
RT2 = R2
\]

\[
VU = RT1 + RT2
\]

\[
VUH = \frac{VU^2}{2g}
\]

PRINT VUH

RETURN

R1 - 0.0
\[
R2 - 0.0
\]
FLOW CHART OF SUBROUTINE CISA

ENTER

DIMENSION STATEMENTS

DO 901 N = 1, M
M: NO. OF ELEMENTS ALONG INNER GATE FACE

JX = 20 + (N-2)

IR = I(JX)
JR = J(JX)
KR = K(JX)

B(IR) = Y(JR)-Y(KR)
C(IR) = X(KR)-X(JR)
B(JR) = Y(KR)-Y(IR)
C(JR) = X(IR)-X(KR)
B(KR) = Y(IR)-Y(JR)
C(KR) = X(JR)-X(IR)

CALCULATE $V_x, V_y, VH$

CALCULATE PRESSURE HEAD PH
PH = TOTAL HEAD - VH

CALCULATE TOTAL FORCE ON THE GATE

CALCULATE DOWNSTREAM VELOCITY HEAD BY MOMENTUM PRINCIPLE

RETURN

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DIMENSION w(133),ps1(y3),Ta(10),Tj(10)
DIMENSION j(133),j(133),k(133),a(133,133),sspscc(j,j,j,j)
DIMENSION c(133),area(133),x(y3),y(93)
DIMENSION d(93),da(10),de(10)

C STIFFNESS MATRIX

READ 11,ma,nm,mb,me,mt

11 FORMAT(6X,6I4)

READ 12,(x(in),y(in),in=1,mt)

12 FORMAT(4X,FS3,4X,FS3)

READ 13,(i(ie),j(ie),k(ie),ie=1,me)

13 FORMAT(I2,4X,I2,4X,1)

READ 16,0,eps1,eps2,g

16 FORMAT(F3.1,FS3,FS3,FS3,FS1)

READ 17,IO,JO,JP

17 FORMAT(6X,FS3,6X,FS3,4X,FS1,5X,FS4)

DO 91 lx=1,8

AN=AO

3N=10

DO 1 lx=1,10

PRINT 18,ao,co

13 FORMAT(1H0,shad=FS3,6X,shad=FS3)

QUE=0.0

DO 93 j3=1,7

N3=J3+43

QUE=QUE+1.0

X(N4)=AO-((AO/10.0)*QUE)

PPI=SQRT(AO*(AO**2-((X(N4)-AO)**2)))

Y(N4)=S-((QO*PPI)/AO)
M = (2*J3) - 1

X(M) = X(NM)

Y(M) = 0.35*Y(NM)

MM = 2*J3

X(MM) = X(NM)

Y(MM) = 0.35*Y(NM)

LM = 91 - J3

X(LM) = X(NM)

Y(LM) = 0.0

833 CONTINUE

X(43) = A0

Y(43) = G - JO

X(93) = X(43)

X(92) = X(43)

X(91) = X(43)

Y(93) = 0.35*Y(43)

Y(92) = 0.15*Y(43)

Y(91) = 0.0

AX = A0

BX = 80

IQ = 3

AN = A0

CC = G - JO

VE = SQRT(2.0*32.2*12.0*(G - CC))

Q = VE*CC

CALL ASA(Q, CC, VE, VUH)

PRINT 87, VUH

87 FORMAT(1H4, 4H = VUH = F10.3)
VI = SQRT(A35(32*2*12.0*2.0*VUH))

Y(66) = Y(66) - VUH
Y(65) = Y(65) - VUH
DEC = (X(63) - X(64)) / (X(63) - X(65))
Y(64) = Y(64) - (DEC*VUH)

DO 9 N=1,21
    M = (2*N) - 1
    PSI(M) = 0.33*O
9 CONTINUE

DO 10 LL=1,21
    L = 2*LL
    PSI(L) = 0.35*O
10 CONTINUE

DO 21 II=1,23
    KL = II + 63
    PSI(KL) = O
21 CONTINUE

DO 22 II=1,23
    KL = II + 63
    PSI(KL) = 0.65*O
22 CONTINUE

PSI(93) = 0.85*O
PSI(67) = PSI(93)
PSI(92) = 0.35*O
PSI(63) = PSI(92)

LL1 = 1
23 IE = 1
24 IR = I(IE)
\[ \begin{align*}
JR &= J(IE) \\
KR &= K(IE) \\
3(\text{IR}) &= Y(\text{JR}) - Y(\text{KR}) \\
C(\text{IR}) &= X(\text{KR}) - X(\text{JR}) \\
3(\text{JR}) &= Y(\text{KR}) - Y(\text{IR}) \\
C(\text{JR}) &= X(\text{IR}) - X(\text{KR}) \\
3(KR) &= Y(\text{IR}) - Y(\text{JR}) \\
C(KR) &= X(\text{JR}) - X(\text{IR}) \\
\text{ARET} &= X(\text{JR}) \times (Y(\text{KR}) - Y(\text{IR})) - X(KR) \times (Y(\text{JR}) - Y(\text{IR})) - \\
& \quad 1 \times (\text{IR}) \times (Y(\text{KR}) - Y(\text{JR})) \\
\text{AREA}(IE) &= \text{ABS}(\text{ARET}) \\
M0 &= 1 \\
IR &= I(IE) \\
IS &= I(IE) \\
IRT &= 1 \\
IST &= 1 \\
26 \text{IPCC}(\text{IRT}, \text{IST}, IE) &= (H(\text{IR}) \times (\text{IS}) + C(\text{IR}) \times C(\text{IS})) / \text{AREA}(IE) \\
\text{GO TO (101, 102, 103, 104, 105, 106, 107)} \\
101 \ IS &= J(IE) \\
\ IST &= 2 \\
\text{GO TO 27} \\
27 \ MO &= M0 + 1 \\
\text{GO TO 26} \\
102 \ \text{IPCC}(\text{IST}, \text{IRT}, IE) &= \text{IPCC}(\text{IRT}, \text{IST}, IE) \\
\ IS &= K(IE) \\
\ IST &= 3 \\
\text{GO TO 27} \\
103 \ \text{IPCC}(\text{IST}, \text{IRT}, IE) &= \text{IPCC}(\text{IRT}, \text{IST}, IE) \\
\end{align*} \]
IS = J(IE)
IST = 2
IR = J(IE)
IRT = 2
GO TO 27
104 IS = K(IE)
IST = 3
GO TO 27
105 B3PCC (IST, IRT, IE) = B3PCC (IRT, IST, IE)
IR = K(IE)
IRT = 3
GO TO 27
106 IE = IE + 1
IF (IE = IE) 24, 24, 28
28 CONTINUE
C ASSEMBLE EQUATION
29 DO 30 IN = 1, MA
W (IN) = 0.0
DO 30 IR = 1, NA
30 A (IN, IR) = 0.0
IN = 1
31 IE = 1
32 IF (I (IE) = IN) 33, 34, 33
33 IF (J (IE) = IN) 35, 36, 35
35 IF (K (IE) = IN) 37, 38, 37
37 IE = IE + 1
IF (IE = IE) 250, 250, 145
250 GO TO 32

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34 IR=1(IE)  
  INT=1  
  IRT=1  
  JR=J(IE)  
  KR=K(IE)  
  GO TO 39
36 IR=J(IE)  
  INT=2  
  IRT=2  
  JR=K(IE)  
  KR=I(IE)  
  GO TO 39
38 IR=K(IE)  
  INT=3  
  IRT=3  
  JR=I(IE)  
  KR=J(IE)  
39 MX=1
140 A(IN,IR)=A(IN,IR)+CCPC(IN,IR,IE)  
  GO TO (141,142,143) MX
141 IR=JR  
142 MX=MX+1  
  IRT=IRT+1  
  IF (IRT=3) 145,148,149
149 IRT=1
146 IF (IR=M) 145,148,149
144 #IN=C(IN)-CCPC(IN,IR,IE) &PSI(IR)  
  GO TO (141,142,143) MX

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142 IR=IR
GO TO 150
143 IF(IE-ME) 37, 145, 145
145 IF(IN-MA) 146, 147, 147
146 IN=IN+1
GO TO 31
147 CONTINUE
C SOLVE FOR PSI(IN)
ITER=1
DO 50 IN=1, MA
50 BO(IN)=OMEGA/A(IN, IN)
BIT=1.0-OMEGA
51 ITER=ITER+1
IF(ITER=IO-) 831, 838, 838
838 PRINT 1000, ITER
1000 FORMAT(1HO, 5HITER=Ib)
GO TO 94
831 CONTINUE
D1=0.0
IN=1
52 EX=0.0
IT=1
IF(V(IN)=0.0) 53, 54, 53
53 EX=V(IN)
54 IF(IT-IN) 276, 55, 55
276 IF(IT-MA) 26, 59, 59
56 IT=IT+1
IF(V(IN, IT)=0.0) 55, 54, 53
55 EX=EX-A(IN,IT)*PSI(IT)

202 IF(IT-MA) 58,59,59

58 IT=IT+1
   IF(A(IN,IT)-0.0) 54,202,54

59 EX=AO(IN)*EX+3IT*PSI(IN)
   IF(ABS(PSI(IN)-EX)-D1) 60,60,61

61 D1=ABS(PSI(IN)-EX)

60 PSI(IN)=EX
   IF(IN-MA) 62,63,63

62 IN=IN+1
   GO TO 52

63 IF(D1-EP) 64,64,51

64 PRINT 55, (PSI(IN), IN=1,MA)

65 FORMAT(1HJ,3HPSI,6F10.3)
   PRINT 1002,ITER

1002 FORMAT(1HJ,5HITER=IE)
   CALL CISA(I,J,K,PSI,UC,Q,AREA,D,G,X,Y,V1,V2)
   EM0=((V2**2)+(32.2*12.0*2.0*CC))/(2.0*32.2*12.0)
   DETAE=EM0-0
   PRINT 14,DETAE

14 FORMAT(1HJ,6HDETAE=F10.5)
   EP=0.0
   DO 66 N=1,10
   M=(2*N)-1
   MM=2*N
   KM=N+42
   KN=KM+1
   IR=I(MM)
JR=J(MM)
KR=K(MM)
B(IR)=Y(JR)-Y(KR)
C(IR)=X(KR)-X(JR)
B(JR)=Y(KR)-Y(IR)
C(JR)=X(IR)-X(KR)
B(KR)=Y(IR)-Y(JR)
C(KR)=X(JR)-X(IR)

GRADX=((B(IR)*PSI(IR))+(B(JR)*PSI(JR))+(B(KR)*
1PSI(KR)))/AREA(MM)
GRADY=((C(IR)*PSI(IR))+(C(JR)*PSI(JR))+(C(KR)*
1PSI(KR)))/AREA(MM)

VM=((GRADX**2)+(GRADY**2))/((64.4*12.0)
XC=(X(IR)+X(JR)+X(KR))/3.
YC=(Y(IR)+Y(JR)+Y(KR))/3.
CANT=(Y(KM)-Y(K))/X(KM)-X(K)
ELT=(CANT*XC)-YC+Y(KM)-(CANT*X(KM))
DSD=SQRT(AJS(1.+(CANT**2)))
DELT=ELT/DSD
XM=(X(KM)+X(K))/2.
AZ=X**-A0
CZ=(30**2)*(AZ**2)
BZ=(A0**2)-(-AZ**2)
DZ=(A0**2)*BZ
EZ=1.+(CZ/DZ)
FZ=(SQRT(AJS(EZ)))**3
AP=10*30
BP=(SQRT(AJS(BZ)))**3
CP=AP/BP
THOU=FZ/CP

\[ VHH = VH \times (1 + (VLT/THOU)^2) \]
\[ YM = \frac{Y(KM) + Y(KN)}{2} \]
\[ EEI = VHH + YM \]
\[ E = EMO \]
\[ EPC = E - EEI \]
\[ SS = EPC^2 \]
\[ EP = EP + SS \]

66 CONTINUE
PRINT 660,EP

660 FORMAT(1H0,3HEP=F20.5)

DA(I)=3.05
DB(I)=3.05
AO=AO+DA(I)
BO=30

Y(66)=Y(66)+VUM
Y(65)=Y(65)+VUM
Y(64)=Y(64)+(DCE*VUM)

1 CONTINUE

tA(LX)=0.05
tB(LX)=0.05
AO=AO-(10.0*0.05)
BO=BO
AO=AO
BO=BO+TB(LX)

91 CONTINUE

94 CALL EXIT
SUBROUTINE FOR CHANGE OF UPSTREAM SURFACE

SUBROUTINE ASA(Q, CC, VE, VUH)

QS=32.2*2.0*12.0*Q
PS=(VE**2)+(32.2*2.0*12.0*CC)
RS=((QS*2)/4.0)-((PS**3)/27.0)
ROOT1=-(QS/2.0)+SQRT(ABS(RS))

IF(ROOT1<3.0) 1,1,2

1 ROT1=ABS(ROOT1)
RO1=ROT1**(1.0/3.0)
RT1=-RO1
GO TO 10

2 RT1=ROOT1**(1.0/3.0)

10 ROOT2=-(QS/2.0)-SQRT(ABS(RS))

IF(ROOT2<3.0) 3,3,4

3 ROT2=ABS(ROOT2)
RO2=ROT2**(1.0/3.0)
RT2=-RO2
GO TO 11

4 RT2=ROOT2**(1.0/3.0)

11 VU=RT1+RT2
VUH=(VU**2)/(32.2*2.0*12.0)
RETURN

END
SUBROUTINE FOR MOMENTUM CALCULATION

SUBROUTINE CISA(I,J,K,PSI,CC,G,AREA,G,X,Y,V1,V2)
DIMENSION I(63),J(63),K(63),S(63),C(63)
DIMENSION PSI(63),PH(10)
DIMENSION YD(10),X(63),Y(63),AREA(40)
DO 931 IY=1,10
JX=20+(IY*2)
IR=I(JX)
JR=J(JX)
KR<K(JX)
B(IR)=Y(JR)-Y(KR)
C(IR)=X(KR)-X(JR)
B(JR)=Y(KR)-Y(IR)
C(JR)=X(IR)-X(KR)
B(KR)=Y(IR)-Y(JR)
C(KR)=X(JR)-X(IR)
GRADX=((B(IR)*PSI(IR))+(B(JR)*PSI(JR))+(B(KR)*
1PSI(KR)))/AREA(JX)
GRADY=((C(IR)*PSI(IR))+(C(JR)*PSI(JR))+(C(KR)*
1PSI(KR)))/AREA(JX)
VH=((GRADX**2)+(GRADY**2))/(64.4*1E0)
YD(IY)=(Y(IR)+Y(JR)+Y(KR))/3.0
PP=0-YD(IY)
PO=PP-VH
PH(IY)=(62.4*PO)/(12.0*3)
931 CONTINUE
SUM=0.0
J0 92 N=1,9
M=N+1
SUM=SUM+(((PH(N)+PH(M))*(YJ(N)-YJ(M)))/2.0)

902 CONTINUE
TRI=((PH(1)*(YJ(1)-G))+(PH(10)*(G-YJ(10)))/2.0
PG=TRI+SUM
PRINT 903,PG

903 FORMAT(1HJ,3HPG=F10.3)
V2=((32.12*(((Y(66)**2)-(CC**2)))-((2.0*PG*32.2*(12.3**4)
1/62.4))/2.0**2)
V2=V2+V1
PRINT 904,V2

904 FORMAT(1HJ,3HV2=F10.3)
RETURN
END
VITA AUCTORIS

1944 Born in Chung-King, China on May 8.

1961 Completed high school in Chien-Kuo High School, Taiwan, China.

1966 Received the degree of Bachelor of Science in Engineering in Hydraulic Engineering from Cheng-Kung University, Taiwan, China.

1970 Currently a candidate for the Degree of Master of Applied Science in Civil Engineering at University of Windsor.