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HYDRODYNAMIC ANALYSIS FOR HIGH-HEAD LEAF GATES[a]

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SYNOPSIS

A one-dimensional analysis of the flow controlled by a high-head gate and of the hydraulic downpull acting on it is presented. The most significant of the flow parameters involved, and a nondimensional term $\overline{\kappa}$ (Kappa) which describes in a complete manner the effect of boundary geometry on the downpull, are evaluated from systematic air-tunnel experiments. The analysis is used as a basis for the presentation of generalized design information. Although it is applied only to the leaf-type gate in this paper, the analysis should prove adaptable also to other types of closure devices for high heads.

Note.—Discussion open until October 1, 1964. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol. 90, No. HY3, May, 1964.

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INTRODUCTION

Leaf gates are among the most widely used high-head gates for flow regulation or emergency closure of large outlets and conduits because of the many advantages they offer in construction and maintenance. Two arrangements may be distinguished: the leaf gate can be operated either in a bonnet or gate well located within a conduit transition [tunnel-type gate, Fig. 1(a)] or on the upstream face of a dam or an intake structure [face-type gate, Figs. 1(b), 1(c), and 1(d)]. In either case, the pressure along the bottom surface of the gate is reduced during operation as a result of the high efflux velocities, whereas the pressure on the upper portion of the gate is only slightly changed from static

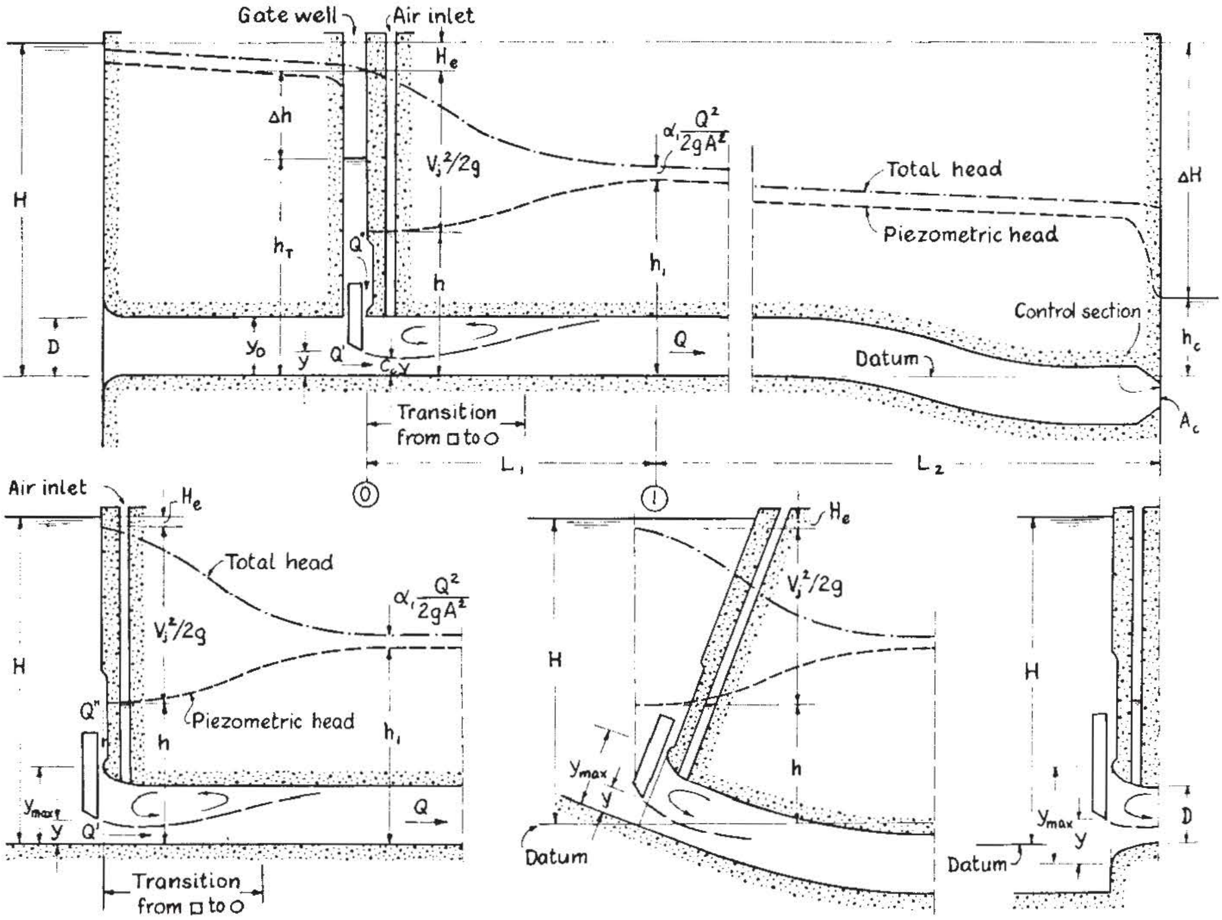

FIG. 1.—SCHEMATIC REPRESENTATION OF TYPICAL LEAF-GATE ARRANGEMENTS UNDER SUBMERGED FLOW CONDITIONS

conditions. The resulting pressure difference induces an unbalanced downward force which often exceeds the dead weight of the gate considerably. Because the magnitude of this force, commonly known as the hydraulic downpull, affects the dimensioning of the hoist mechanism and, hence, the safety of the entire project, its prediction has been, and still is, of major concern to hydraulic engineers.

Although extensive downpull studies have been conducted in the past (Appendix II-A), there is no satisfactory method available for adapting these findings to new projects in more than a qualitative manner, and specific model tests are still indispensable. The difficulty in applying previous experimental work lies in the fact that not only the boundary geometry, but also the flow conditions under which the gate is operated, vary from project to project. Based on initial analytical work, (A16 and A18),[4] and continued investigations conducted at the Iowa Institute of Hydraulic Research, the present paper is intended to provide a framework for the generalization of experimental downpull data by analyzing separately the effects of geometry and flow conditions on the downpull.

The main portion of the downpull results from the difference between the pressure forces acting on the top and bottom surfaces of the gate, the residual portion acts on the seals and other protrusions of the gate. Essential for the downpull analysis, hence, is the prediction of the pressure forces effective on the top and on the bottom of the gate, each of which can be expressed by the ratio $\bar{\kappa}$ of the respective mean piezometric head to a reference velocity head. The significance of the $\bar{\kappa}$-terms so obtained is their independence of the absolute magnitude of the flow velocities. Once determined they can be used in combination with any flow condition so long as the boundary geometry is similar, provided the Reynolds number is sufficiently high. This condition is usually satisfied for high-head gates. The downpull analysis is thus reduced to the evaluation of the $\bar{\kappa}$-terms for a particular geometry configuration and the determination of the reference velocity head for a particular flow condition.

The latter part of the problem is approached semi-empirically. By the one-dimensional method of analysis an equation is derived expressing the rate of flow past the gate as a function of the gate opening and width, the total head over the conduit inlet, and the conditions of control in the conduit downstream from the gate. Such effects upon the rate of flow as stem from the flow contraction at the gate, the entrance head loss, the shape and the surface roughness of the transition downstream from the gate, or the fact that water may also be released through a recess of the concrete face opposite to the top seal, are considered with the aid of empirical coefficients. Except for the contraction coefficient, they prove to be of relatively small importance in the evaluation of the rate of flow, so that good results are obtained even with the coefficients only approximated.

Information as to the $\bar{\kappa}$-terms and the empirical coefficients previously mentioned (all functions of the gate and conduit geometry) has necessarily to be derived from experiments. The main results from air-tunnel tests, conducted at the Iowa Institute of Hydraulic Research on an idealized two-dimensional model of a high-head gate, are presented as a first contribution toward a generalized presentation of such data. The studies are being continued. The idealization was adopted in order to distinguish clearly the relative influence of such primary boundary variables as the inclination of the bottom surface of the gate and the rounding of its upstream edge, the possible projection of the gate lip, the gate thickness relative to the conduit height, and the gate opening. In addition, it permits certain conclusions relative to the susceptibility of a given geometry of the gate lip to cavitation and vibration. The paper concludes with a comprehensive bibliography on topics related to the hydraulics of high-head gates.

Notation.—Letter symbols adopted for use in this paper are defined where they first appear and listed alphabetically in Appendix I.—Notation.

[4] Numerals in parentheses refer to corresponding items listed in Appendix II.—Bibliography.

FLOW ANALYSIS

Two states of flow may be distinguished—the free-surface case, in which the jet of water issues from the gate with a free surface, and the submerged case, in which the jet is drowned by a standing eddy. The transition from one state of flow to the other occurs as a hydraulic jump approaches or withdraws from the gate. The corresponding intermittent state of partially submerged flow is limited to an extremely small range of gate openings and has therefore been omitted in the following analysis.

Submerged Flow.—For most installations of high-head gates the state of submerged flow is predominant during their operation. The line of total head and the line of piezometric head for both tunnel-type and face-type gates under submerged conditions are illustrated in Fig. 1. If the head losses involved between reservoir and gate section are summarized by means of one over-all entrance loss H_e in the form

$$H_e = C_e \frac{1}{2 g} \left(\frac{Q}{A}\right)^2 \quad \text{(1)}$$

then the rate of flow Q' released by the gate is obtained from the one-dimensional energy relationship as

$$Q' = a' A \sqrt{2g \left(H - H_e - h\right)} \quad \text{(2)}$$

in which

$$a' = \frac{C_c\, y\, b}{A} \quad \text{(3)}$$

is the ratio of the cross-sectional area C_c y b of the fully contracted jet to the area A of the conduit section, and H and h are the total head in the reservoir and the piezometric head at any point in the contracted jet, respectively, both referred to a common datum. The velocity distribution in the contracted section of the jet is assumed to be uniform.

Most of the recent high-head outlet works provide a recess in the concrete face opposite to the top seal of the gate through which water is released during gate operation at the rate

$$Q'' = C A_2 \sqrt{2 g \left(H - H_e - h\right)} \quad \text{(4)}$$

if it is assumed that the jet, issuing from the gap between the downstream face of the gate and the downstream wall of the gate chamber, has a cross-sectional area A2 and a piezometric head h at its fully contracted section. The symbol C denotes a discharge coefficient.

The total rate of flow past the gate can now be written

$$Q = Q' + Q'' = a A \sqrt{2 g \left(H - H_e - h\right)} \quad \text{(5)}$$

with

$$a = \frac{(C_c\ y\ b + C\ A_2)}{A} \qquad (6)$$

The impulse-momentum relationship, if integrated in the direction of the conduit axis over the reach between section (0) of the contracted jet and section (1), takes the form

$$F_0 - F_1 - F_2 - F_s = \rho\beta_1 \frac{Q^2}{A} - \rho \frac{(Q')^2}{a'\ A} \qquad (7)$$

in which force due to pressure in section (0) is

$$F_0 = \gamma \left(\frac{h - y_{max}}{2}\right) b\ y_{max} \qquad (8a)$$

the force due to pressure in section (1) is

$$F_1 = \gamma \left(\frac{h_1 - D}{2}\right) A \qquad (8b)$$

and force due to pressure on the vertical projection of the transition walls between sections (0) and (1) is

$$F_2 = F_0 - \gamma \left(\frac{h - D}{2}\right) A + \gamma\ (h_1 - h)\ (by_{max} - A)\ \frac{\zeta}{2} \qquad (8c)$$

In addition ζ refers to the factor compensating for the assumption of hydrostatic pressure distribution in the transition between sections (0) and (1), (for long transitions $\zeta \to 1$, for short ones $\zeta \to 0$), and the factor compensating for the use of the mean velocity in section (1) is defined by

$$\beta_1 = \left(\frac{1}{A}\right) \int_A \left(\frac{v_1}{V_1}\right)^2 dA \qquad (9)$$

The momentum of the flow Q" is not included, because it is directed perpendicular to the axis of the conduit. The component F_s of the force due to boundary shear in the reach between section (0) and (1) acting in the direction of the conduit axis can be approximated, when using the Darcy-Weisbach resistance formula, as

$$F_s = \gamma\ A_m\ (h_f)_m = \gamma\ A_m f\ \frac{L_1}{4\ R_m}\ \frac{V_m^2}{2g} \qquad (10)$$

in which A_m is the average cross-sectional area of the flow passage and V_m the average mean velocity. If the average effective hydraulic radius R_m in the reach between sections (0) and (1) is approximated by

$$R_m = \frac{A\ (1 + a')}{b + 2y + \pi D} = \frac{D}{4} \frac{1 + a'}{N} \quad \text{.......... (11)}$$

N being a parameter for the average wetted perimeter,

$$N = \frac{(\pi\ D + b + 2\ y)}{\pi\ D} \quad \text{................(12)}$$

and Eqs. 2 and 5 are substituted, F_s becomes

$$F_s = f \frac{L_1}{D} \frac{N}{8} (1 + a)^2\ \gamma\ A\ \left(H - H_e - h\right) \quad \text{........(13)}$$

and Eq. 7 results in

$$H - H_e - h = \frac{H - H_e - h_1}{1 + \left[\frac{\left(\beta_1\ a^2 - a'\right)2}{K}\right] + (1 + a)^2\ f \left(\frac{L_1}{D}\right) \frac{N}{K}} \quad \text{..(14)}$$

in which K combines the terms

$$K = 1 + \frac{\zeta}{2} \left(\frac{b\ y_{max}}{A} - 1\right) \quad \text{................(15)}$$

The piezometric head h_1 in section (1) follows from the one-dimensional energy relationship applied to the sections (1) and (c), the latter being the section of downstream control generally located at the conduit outlet [Fig. 1(a)],

$$h_1 - h_c = \frac{Q^2}{2g} \left[\frac{\alpha_c}{A_c^2} - \frac{\alpha_1}{A^2} + f \frac{L_2}{D\ A^2} + \Sigma\ \frac{C_L}{A^2}\right] \quad \text{.......(16)}$$

The last two terms to the right of Eq. 16 represent the surface resistance and the sum of local head losses in the reach between sections (1) and (c), and

$$\alpha = \frac{1}{A} \int_A \left(\frac{v}{V}\right)^3 dA \quad \text{................(17)}$$

is a factor compensating for the use of the mean velocity.

For the gate completely withdrawn, the energy equation becomes

$$H - h_c = \Delta H = \frac{Q_{max}^2}{2\,g}\left[\frac{C_e}{A^2} + \frac{\alpha_c}{A_c^2} + f\,\frac{L_1 + L_2}{D\,A^2} + \Sigma\,\frac{C_L}{A^2}\right] \quad \ldots (18)$$

if the average hydraulic radius in the reach between sections (0) and (1) is approximated by D/4 in this case. Introducing the ratio of the rate of flow Q_{max} at the maximum gate opening to the theoretical rate of flow for zero head loss

$$C_0 = \frac{Q_{max}}{A\,\sqrt{2\,g\,\Delta H}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

which is an important design characteristic for any specific project, and substituting Eq. 5 into Eqs. 16 and 13, yields

$$h_1 - h_c = a^2\left[\frac{1}{C_0^2} - \alpha_1 - C_e - \frac{f\,L_1}{D}\right]\left(H - H_e - h\right) \quad \ldots (20)$$

It becomes apparent from this equation that the total head loss downstream from section (1) is taken into account by C_0.

With reference to Fig. 1 and through application of Eqs. 1, 14, and 20, the velocity head in the contracted jet under the gate is expressed as

$$\frac{V_j^2}{2\,g} = H - H_e - h = C_d^2\,\Delta H \quad \ldots\ldots\ldots\ldots (21)$$

in which

$$C_d = \frac{1}{\sqrt{1 + a^2\left[\left(\frac{2\,\beta_1}{K}\right) + \left(\frac{1}{C_0^2}\right) - \alpha_1\right] - \left[\frac{2\,a'}{K}\right] - \left[a^2 - (1 + a)^2\,\frac{N}{8\,K}\right]\frac{f\,L_1}{D}}} \quad \ldots (22)$$

may be defined as a discharge coefficient since

$$C_d = \frac{Q}{(a\,A\,\sqrt{2\,g\,\Delta H})} \quad \ldots\ldots\ldots\ldots\ldots\ldots (23)$$

With the aid of Eq. 19, the following significant flow characteristics are obtained:

$$\frac{Q}{Q_{max}} = \frac{a\ C_d}{C_0} \qquad (24a)$$

$$\frac{Q'}{Q_{max}} = \frac{a'\ C_d}{C_0} \qquad (24b)$$

and

$$\frac{Q''}{Q_{max}} = \frac{(a - a')\ C_d}{C_0} = \left(\frac{C\ A_2}{A}\right) \frac{C_d}{C_0} \qquad (24c)$$

Free-Surface Flow.—If a jet with free surface issues from the gate, air will become entrained in the water and ventilation through an air inlet must be provided if cavitation and vibration are to be avoided. The piezometric head in the contracted section of the jet will then be

$$h^* = C_c\ y + \frac{\Delta p}{\gamma} \qquad (25)$$

in which Δp is the difference between the pressure of the air downstream from the gate and the atmospheric pressure at the reservoir ($\Delta p \leq 0$), which depends on the amount of air entrained by the jet and the dimensioning of the air inlet and can be determined with the aid of the references in Appendix II-D. The rate of flow under the gate becomes, for the state of free-surface flow,

$$Q' = C_c\ y\ b\sqrt{2\ g\left(H - H_e - h^*\right)} \qquad (26)$$

and the discharge coefficient C_d, which was defined as $Q/(a\ A\sqrt{2\ g\ \Delta H})$ or $V_j/\sqrt{2\ g\ \Delta H}$, becomes

$$C_d = \sqrt{\frac{H}{\Delta H}}\sqrt{\frac{1 - \frac{h^*}{H}}{1 + a^2\ C_e}} \qquad (27)$$

using for simplicity $Q/a = Q'/a'$, a relationship which applies only approximately to free-surface flow unless $h^* = y_2 + \Delta p/\gamma$.

If y_2 denotes the vertical distance from the datum to the fully contracted section of the jet issuing from the gate chamber, the rate of flow Q'' can be written

$$Q'' = C\ A_2\sqrt{2\ g\left(H - H_e - y_2 - \frac{\Delta p}{\gamma}\right)} \qquad (28)$$

provided that the vapor pressure is not reached at any point of the flow passage. [The limitations imposed by this condition have been previously examined (A16, p. 430.)]

In a more significant form, the rates of flow can be expressed as

$$\frac{Q'}{Q_{max}} = \frac{a'}{C_0\sqrt{\frac{\Delta H}{H}}}\sqrt{\frac{\frac{1 - h^*}{H}}{1 + a^2 C_e}} \qquad (29a)$$

and

$$\frac{Q''}{Q_{max}} = \frac{\frac{C A_2}{A}}{C_0\sqrt{\frac{\Delta H}{H}}}\sqrt{\frac{\frac{1 - y_2 + \frac{\Delta p}{\gamma}}{H}}{1 + a^2 C_e}} \qquad (29b)$$

Analysis.—The derived equations apply without difference to tunnel-type and face-type gates. As proved previously (A16), the equations may also be applied to the special cases of face-type gates represented in Fig. 1(c) and 1(d), if the datum is chosen as indicated.

The functional relationship of the most significant flow parameters, C_d and Q/Q_{max}, for the free and the submerged state of flow, is illustrated by Figs. 2, 4, and 5. (The conditions for the curves of Fig. 2 are $N = 2$, $A_2 = f = h^* = 0$, $\alpha_1 = \beta_1 = K = 1$. For Fig. 4 $N = 2$, $A_2 = f = 0$, $\alpha_1 = \beta_1 = K = 1$.) The transition from one state of flow to the other is defined in Fig. 2 by the intersection of the curves which are pertinent to the respective flows. The condition that the jet velocity V_j can never exceed the value corresponding to free efflux determines which of the two pertinent curves applies for a particular gate opening. It is interesting to note in this regard that for $\Delta H/H \ll 1.0$ and C_0 close to unity the free efflux is either physically impossible or limited to intermediate gate openings. With $\Delta H/H$ being generally greater than unity, the free efflux is restricted to small gate openings within a range which becomes narrower with decreasing C_0.

Part of the complexity of the flow analysis stems from the compensation for the use of mean velocities and hydrostatic pressure distributions and from the consideration of boundary resistance by appropriate parameters. The effect of the respective parameters α_1, β_1, K, and fL_1/D on the rate of flow is illustrated in Figs. 3(b), 3(c), and 3(d) (for extreme departures from the ideal condition $\alpha_1 = \beta_1 = K = 1.0$ and $f = 0$). As is apparent from these graphs, the rate of flow becomes more effected by these quantities as C_0 is increased. It should be noted that α_1 and β_1 are functions of L_1 and of a'. The percentage increase of C_d according to the dotted line in Fig. 3(b) could actually never

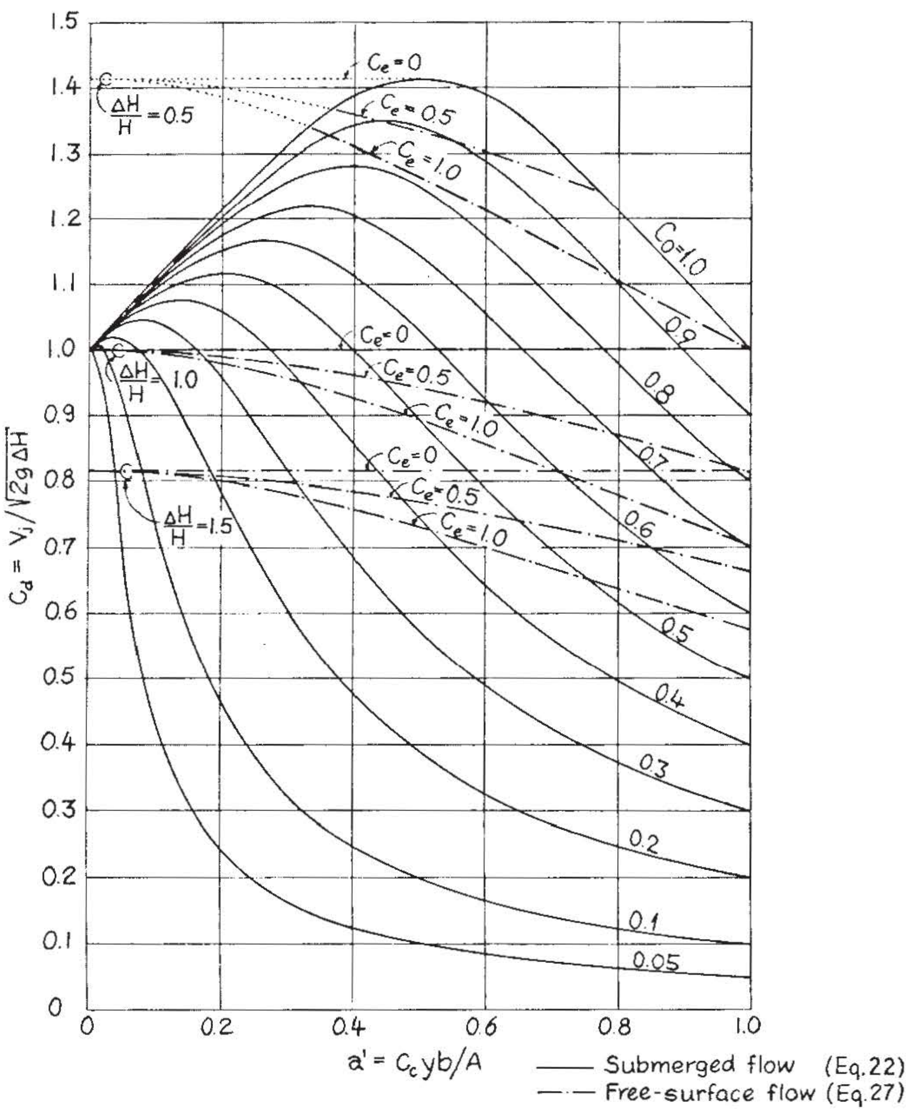

FIG. 2.—VARIATION OF DISCHARGE COEFFICIENT C_d WITH RELATIVE GATE OPENING a'

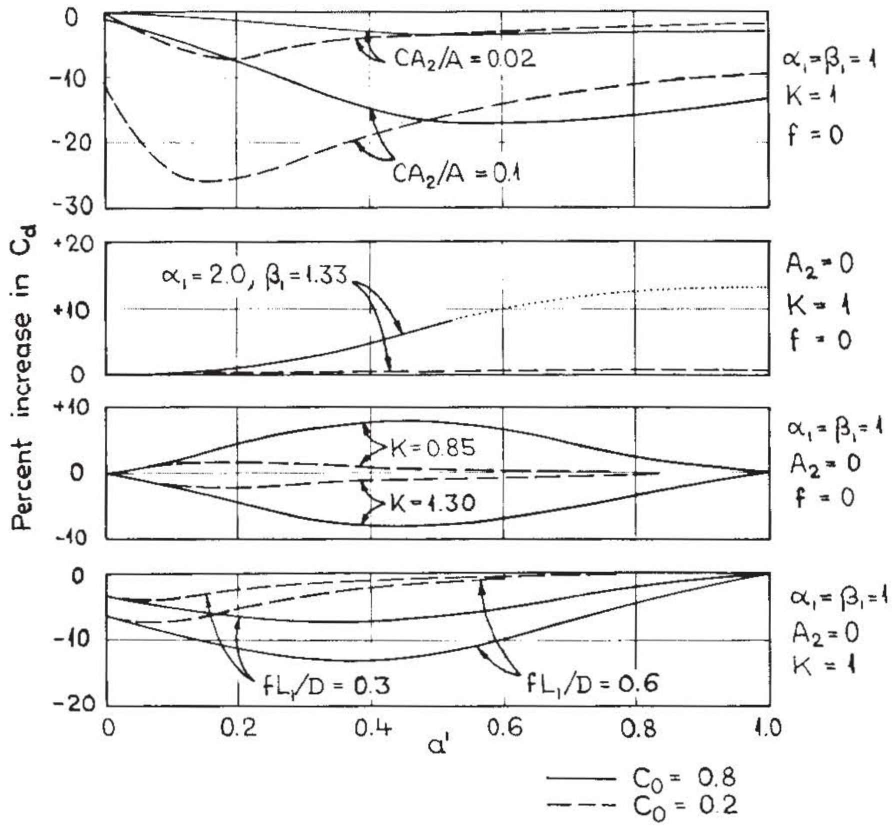

FIG. 3.—EFFECT OF SOME EMPIRICAL QUANTITIES ON THE DISCHARGE COEFFICIENT FOR SUBMERGED FLOW

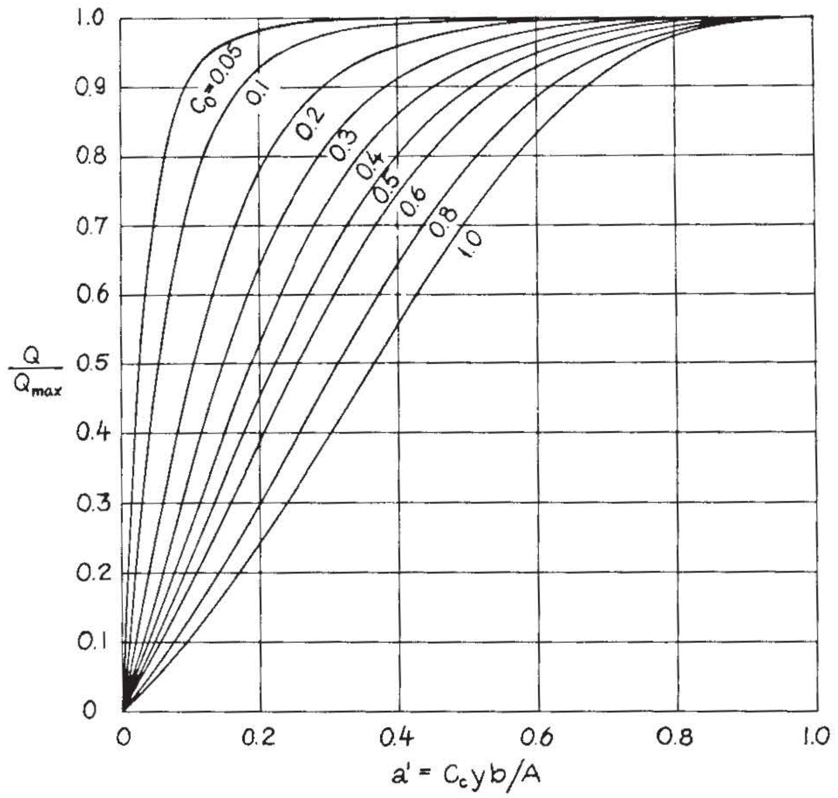

FIG. 4.—VARIATION OF Q/Q_{max} WITH RELATIVE GATE OPENING a' FOR SUBMERGED FLOW

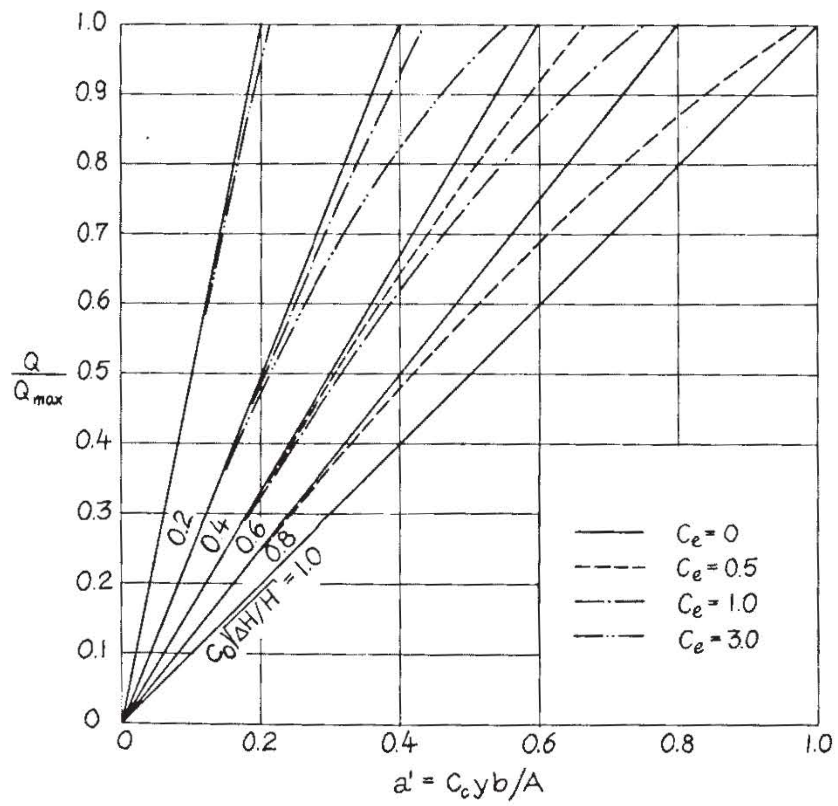

FIG. 5.—VARIATION OF Q/Q_{max} WITH RELATIVE GATE OPENING a' FOR FREE-SURFACE FLOW

occur, because α_1 and β_1 tend toward moderate values for uniform conduit flow[5] as a' tends toward unity.

The deviation from the mean of the velocities across the contracted jet and the departure from hydrostatic pressure distribution in sections (0) and (1) are ignored in the analysis. They could have been compensated for by introducing α_0 and β_0 and expanding the expression for K. However, the increased complexity would have resulted in an insignificant gain in accuracy.

Another source of complication in the analysis is the flow above the gate, the rate of which has been expressed with the aid of A_2 and C. To facilitate the determination of these quantities it is advisable to create, by appropriate design, conditions for the flow through gate chamber and gate slots that can be better analyzed. It was to this end, for example, that in the Garrison Dam project (A12) water was prevented from passing through the gate slots by means of horizontal steel plates attached to either side of the gate.

Information with respect to the discharge coefficient C for the face-type gate is obtained from Naudascher's previous work (A16). For the tunnel-type gate C can be derived as follows. With reference to Fig. 1(a)

$$Q'' = C_1\ A_1\sqrt{2\ g\ \left(H - H_e - h_T\right)} = C_2\ A_2\sqrt{2\ g\ \left(h_T - h\right)} \quad \ldots (30)$$

in which A_1 depicts the minimum cross-sectional area of the upstream passage between gate and gate chamber, C_1 and C_2 are local discharge coefficients associated with the flow through the upstream and downstream passages, respectively, and h_T is the piezometric head on the top surface of the gate. By eliminating h_T from Eq. 30

$$C = \frac{C_2}{\sqrt{1 + \left(\frac{C_2\ A_2}{C_1\ A_1}\right)^2}} \quad \ldots\ldots\ldots\ldots\ldots (31)$$

A significant parameter for the flow conditions above the gate is obtained in the combination of terms CA_2/A. Its influence on the total rate of flow is illustrated by Fig. 3(a).

DOWNPULL ANALYSIS

For steady, irrotational flow the piezometric head along a boundary is completely defined by the distribution of velocity along the boundary relative to a reference velocity v_0 and by the magnitude of the latter.[6] The distribution of relative velocity v/v_0 and, hence, the distribution of piezometric head relative to the reference magnitude $v_0^2/2\ g$ as well, depend entirely on the flow pattern or the several geometric parameters characterizing it. It follows that the relative distribution of piezometric head is independent of the actual linear scale and the actual magnitude of velocity.

5 Rouse, H. (Editor), "Engineering Hydraulics," John Wiley & Sons, Inc., New York, N. Y., 1950, p. 401, Fig. 9.

6 Ibid., p. 27.

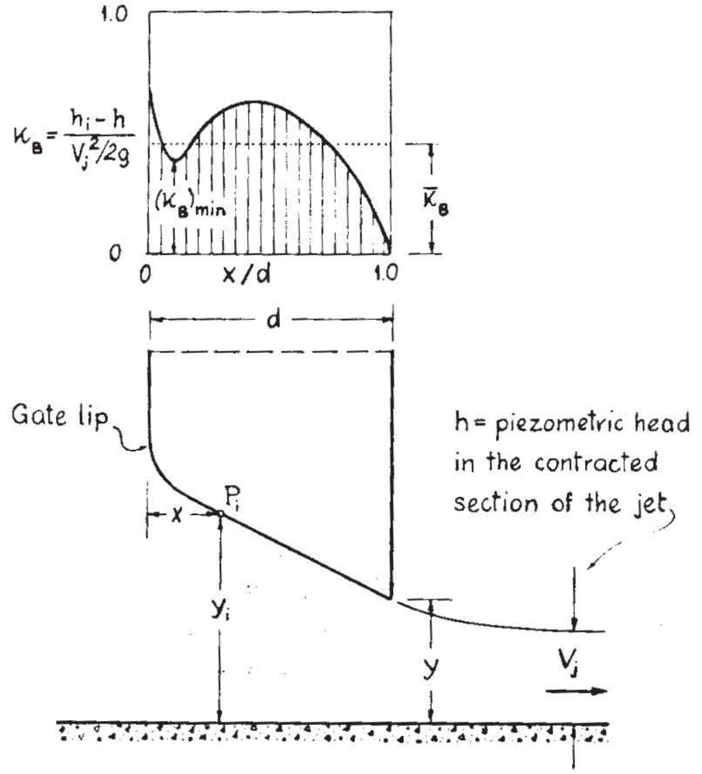

FIG. 6.—DEFINITION SKETCH FOR THE LOCAL AND MEAN VALUES OF κ_B

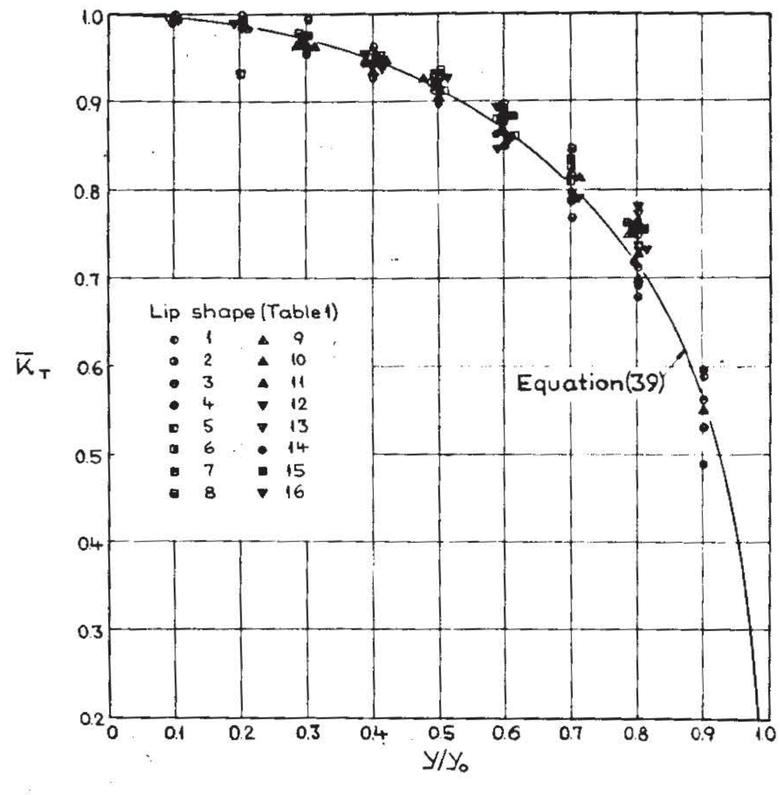

FIG. 7.—VARIATION OF κ_T WITH RELATIVE GATE OPENING y/y_0 FOR A TUNNEL-TYPE GATE, THE TOP OF WHICH IS SEALED ON THE DOWNSTREAM SIDE

In general, the flow along the bottom surface of a high-head gate is continuously accelerated, in which case the departure from the conditions of irrotational flow is negligible. Consequently, if $V_j^2/2\,g$ is selected as a significant reference,

$$\kappa_B = \frac{\left(\frac{p_i}{\gamma}\right) + y_i - h}{\frac{V_j^2}{2\,g}} = \frac{h_i - h}{\frac{V_j^2}{2\,g}} \quad \text{.............. (32)}$$

should also be independent of the actual magnitude of velocities, and it should be possible to relate a particular pressure distribution under the gate uniquely to a corresponding gate and conduit geometry (Fig. 6). The difference $(h_i - h)$ of the piezometric heads at a point on the bottom surface of the gate and at a point of the fully contracted jet, respectively, rather than h_i is used in Eq. 32 in order to signify stagnation conditions by the value $\kappa_B = 1.0$. Integration of the relative distribution of piezometric head with respect to the gate thickness and the gate width yields

$$\bar{\kappa}_B = \frac{1}{B\,d}\int_0^d\int_0^B \frac{h_i - h}{\frac{V_j^2}{2\,g}}\, dB\, dx \quad \text{............. (33)}$$

Since the distribution of the piezometric head h_T on the top surface of the gate is generally constant, it can readily be integrated to yield

$$\bar{\kappa}_T = \frac{1}{B\,d}\int_0^d\int_0^B \frac{h_T - h}{\frac{V_j^2}{2\,g}}\, dB\, dx \approx \frac{h_T - h}{\frac{V_j^2}{2\,g}} \quad \text{.......... (34)}$$

Substituting the piezometric heads h and h_T from the equations

$$\frac{h}{\frac{V_j^2}{2\,g}} = \frac{H}{C_d^2\,\Delta H} - 1 - a^2\,C_e \quad \text{............ (35a)}$$

and

$$\frac{h_T}{\frac{V_j^2}{2\,g}} = \frac{H}{C_d^2\,\Delta H} - 1 - a^2\,C_e + \frac{1}{1 + \left(\frac{C_2\,A_2}{C_1\,A_1}\right)^2} \quad \text{...... (35b)}$$

which are obtained from the flow analysis, the mean relative piezometric head on the top surface of the gate becomes

$$\bar{\kappa}_T = \frac{1}{1 + \left(\frac{C_2 A_2}{C_1 A_1}\right)^2} \qquad (36)$$

The trend of this relationship is represented in Fig. 8. For the face-type gate, being characterized by $A_1 = \infty$, $\bar{\kappa}_T$ is equal to unity. For the tunnel-type gate, the validity of Eqs. 35b and 36 is restricted to irrotational-flow conditions, as will be examined subsequently.

Knowledge of the pertinent $\bar{\kappa}$-values and the reference velocity V_j will, finally, permit determination of the corresponding downpull. The primary portion of the downpull, resulting from the difference of the integrated distri-

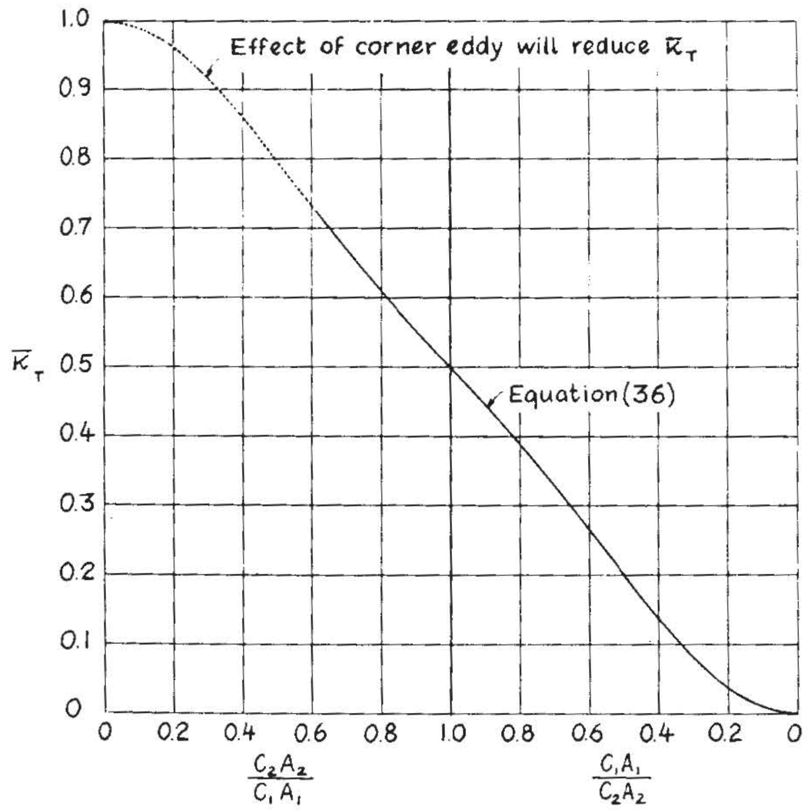

FIG. 8.—EFFECT OF THE FLOW AROUND THE TOP OF A TUNNEL-TYPE GATE ON κ_T

butions of piezometric head along the top and the bottom surface of the gate, becomes

$$P_1 = \left(\bar{\kappa}_T - \bar{\kappa}_B\right) B\, d\, \rho \frac{V_j^2}{2} \qquad (37)$$

The residual portion of the downpull stems from the difference in pressure acting on such horizontal protrusions of the gate as the top seal. If no water

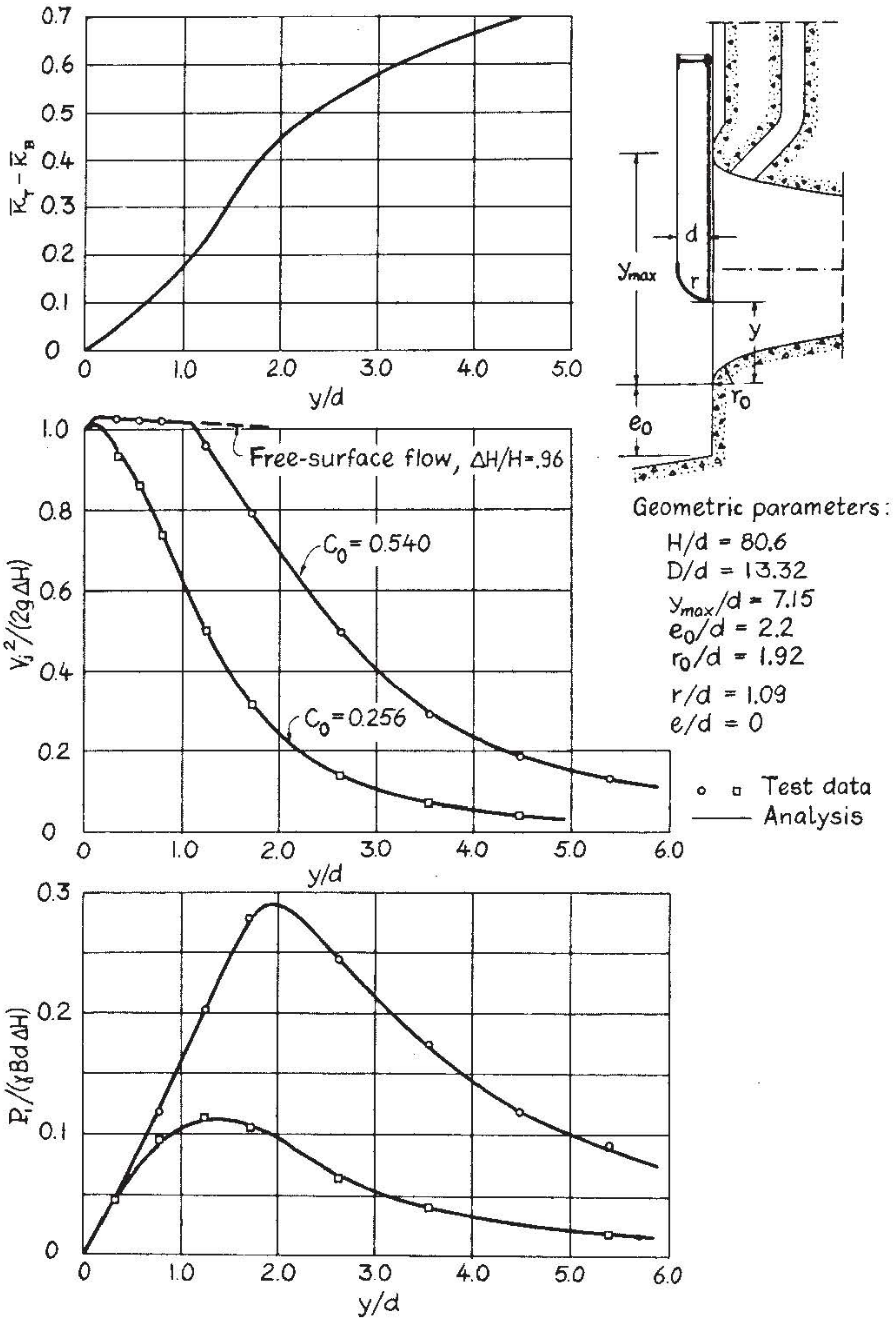

FIG. 9.—EXAMPLE OF DOWNPULL ANALYSIS (A18)

is released above the gate ($A_2 = 0$) and the area of the horizontal projection of the top seal is denoted by A_S, the downpull on the top seal can be written as

$$P_2 = \gamma \; A_s \left(h_T - h\right) = \bar{\kappa}_T \; A_s \; \rho \; \frac{V_j^2}{2} \quad \ldots\ldots\ldots\ldots (38)$$

If, on the other hand, a recess is placed in the face opposite to the seal ($A_2 \neq 0$), the water flowing around the top seal acts to equalize the pressures on the upper and lower sides of the seal and thus to eliminate that part of the downpull. An additional force $P_3 \approx \bar{\kappa}_T B d' \rho V_j^2/2$ will act in the case of a lip shape with an extended skinplate [Fig. 10(a)]. For forces on standard bottom seals see reference A9.

Analysis.—An example is given in Fig. 9 demonstrating how the downpull is determined if the $\bar{\kappa}$-values and the velocity V_j are known from experiment and flow analysis, respectively. In the non-dimensional form $P_1/(\gamma B d \Delta H)$ the downpull is obtained for a particular gate opening by multiplying the corresponding quantities $(\bar{\kappa}_T - \bar{\kappa}_B)$ and $V_j^2/(2 g \Delta H)$ of the upper two graphs. As seen from the agreement between analysis and test data, the use of one $(\bar{\kappa}_T - \bar{\kappa}_B)$-curve in combination with two different flow conditions, characterized by C_0, leads to the correct value of the downpull, indicating that the $\bar{\kappa}$-values are indeed independent of the absolute flow velocities. The condition of quasi-irrotational flow upstream from and underneath the gate is, of course, satisfied in this case.

As the flow along the upstream boundaries of a gate departs from irrotational conditions due to local deceleration, the flow may separate and thus create new boundary conditions. The mean piezometric head ratios $\bar{\kappa}$ will then no longer depend on the boundary geometry alone, but also on the Reynolds number **R** of the flow. Experiments indicate, however, that the relative distribution of piezometric head tends to become independent of the Reynolds number for higher values of **R** (see Fig. 12 which is for lip shape no. 3, y/y_0 = 0.4). Since **R** is sufficiently high in practically all high-head installations, the $\bar{\kappa}$-values should be uniquely predictable for a given boundary form even in cases of local flow separation. Fig. 13 shows the flow pattern along the gate bottom, (for lip shape no. 3 $y/y_0 = 0.4$ and $\mathbf{R} = 2 \times 10^5$) viewed from below.

An interesting example of local flow separation is the corner eddy upstream from a tunnel-type gate. According to the concept of irrotational flow, stagnation pressure should be attained in the corner between the conduit roof and the upstream face of the gate. In reality, the pressure is reduced by the action of a quasi-steady eddy. With water flowing around the top of the gate ($A_2 \neq 0$) the adverse pressure gradient in the corner, and thus the eddy, may eventually be eliminated in a process analogous to boundary layer suction. It is for this condition that Eqs. 35b and 36 apply correctly (Fig. 8). Usually a combined effect due to flow around the gate top (Fig. 8) and due to the corner eddy (Fig. 7) will prevail in a range of small to moderate ratios of $C_2 A_2/C_1 A_1$. If no water is released above the gate ($A_2 = 0$) the corner eddy will reduce the stagnation pressure (represented by $\bar{\kappa}_T = 1.0$) as shown in Fig. 7. Interestingly enough, the various experimental results in this figure are closely described by

$$\bar{\kappa}_T = \frac{1 - C_c}{1 - (C_c)_0} \qquad (39)$$

in which C_c is the coefficient of jet contraction for a slot in a wall perpendicular to the conduit after von Mises[7] and $(C_c)_0$ is the same for a slot-width equal to zero ($y/y_0 = 0$). The changes in $\bar{\kappa}_T$ with Reynolds-number in the range $0.7 \times 10^5 < \mathbf{R} < 2 \times 10^5$ were found to be less than 1%.

The magnitude of the downpull can be controlled in two ways: Through $\bar{\kappa}_B$ by the design of the gate lip, and through $\bar{\kappa}_T$ by the dimensioning of the flow

[7] Ibid., p. 34.

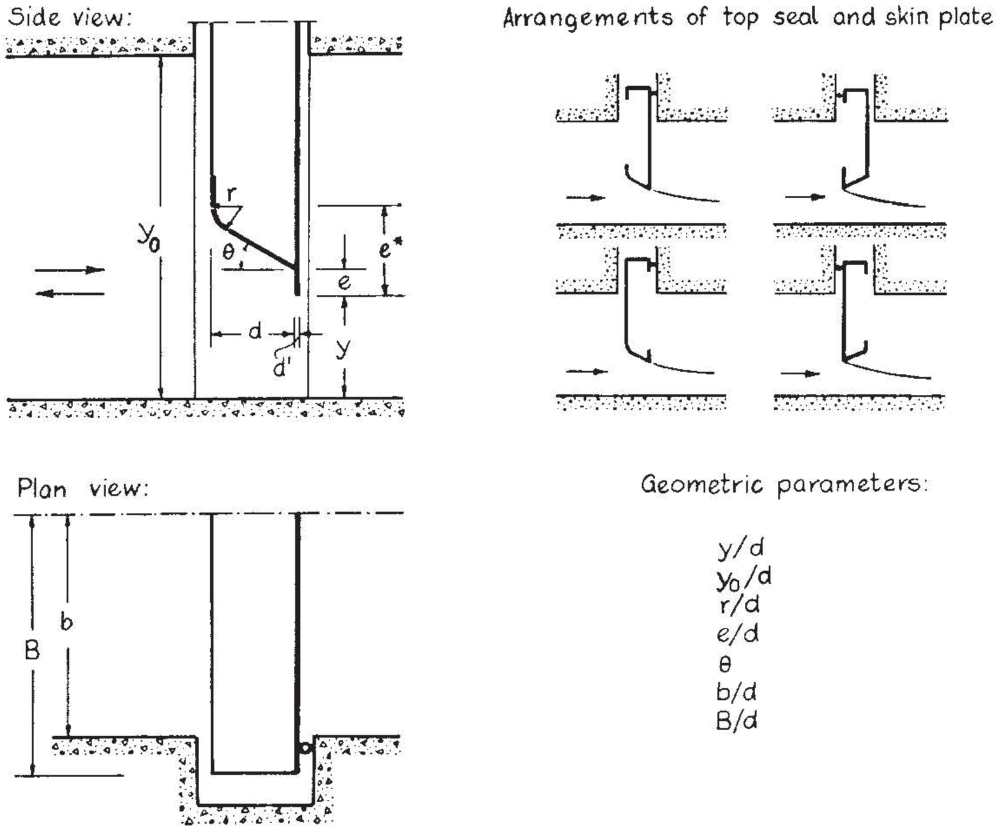

FIG. 10.—DEFINITION SKETCH OF COMMON GEOMETRY PARAMETERS AND POSSIBLE TOP-SEAL AND SKINPLATE ARRANGEMENTS FOR HIGH-HEAD LEAF GATES

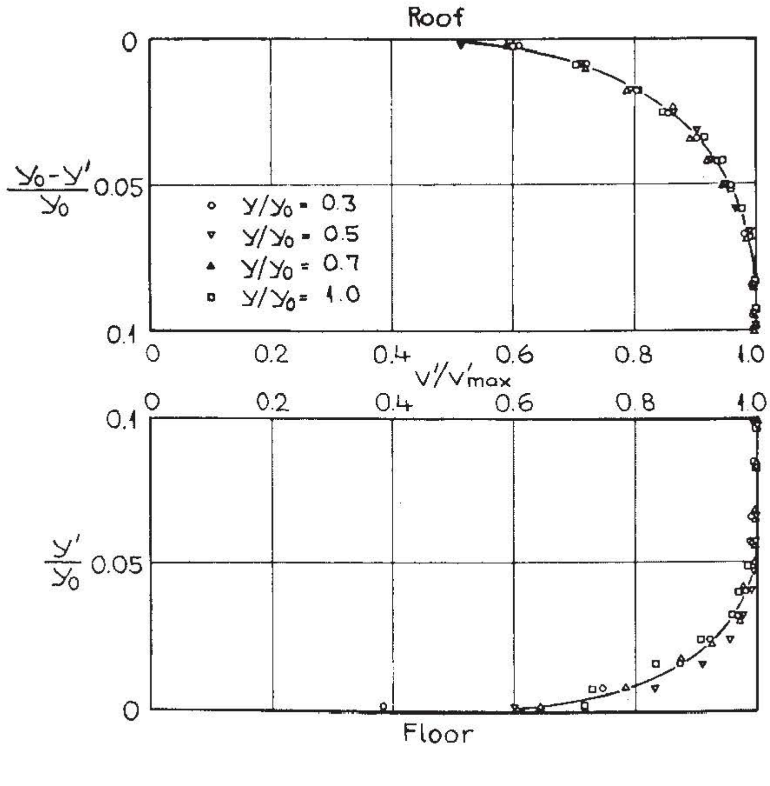

FIG. 11.—DISTRIBUTION OF THE VELOCITY AT A SECTION 16 d UPSTREAM FROM THE GATE FOR **R** = 2 x 10^5 AND y_0/d = 6

TABLE 1.—INVESTIGATED COMBINATION'S OF GEOMETRY PARAMETERS

No.	θ, in degrees	r/d	e/d	e*/d	y_0/d
1	45	0.4	0	1.17	6.0
2	30	0.4	0	0.81	6.0
3	20	0.4	0	0.64	6.0
4	0	0.4	0	0.40	6.0
5	0	0.4	0.15	0.55	6.0
6	0	0.4	0.30	0.70	6.0
7	0	0.4	0.45	0.85	6.0
8	0	0.4	0.60	1.0	6.0
9	0	0.2	0.15	0.35	6.0
10	0	0.2	0.30	0.50	6.0
11	0	0.2	0.45	0.65	6.0
12	0	0.6	0.30	0.90	6.0
13	0	0.6	0.45	1.05	6.0
14	30	0.4	0	0.81	4.0
15	0	0.4	0.45	0.85	4.0
16	0	0.2	0.15	0.35	4.0
17	30	0.4	0	0.81	8.0
18	0	0.4	0.45	0.85	8.0
19	0	0.2	0.15	0.35	8.0
20	30	0.4	0	0.81	12.0
21	30	0.4	0	0.81	20.0

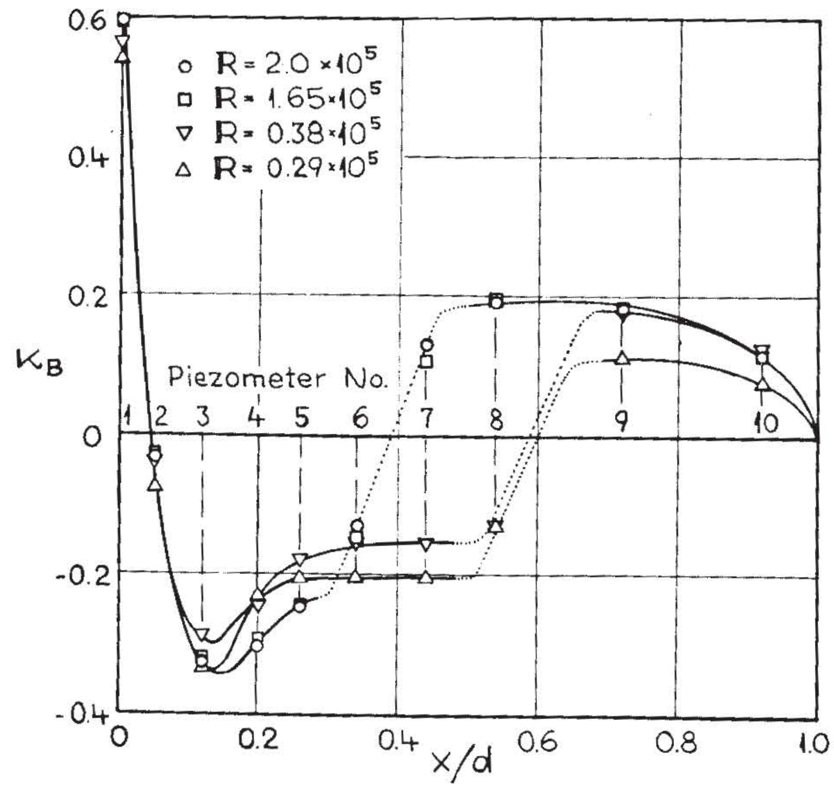

FIG. 12.—VARIATION IN THE DISTRIBUTION OF RELATIVE PIEZOMETRIC HEAD WITH REYNOLDS-NUMBER

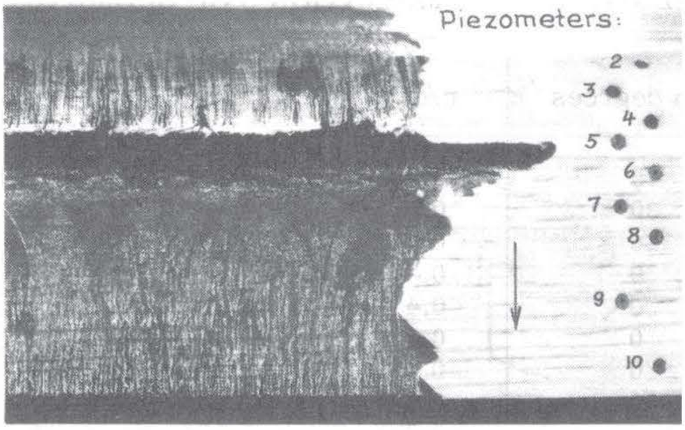

FIG. 13.—FLOW PATTERN ALONG THE GATE BOTTOM AT $\mathbf{R} = 2 \times 10^5$, VIEWED FROM BELOW

passages around the upper portion of the gate. The latter control is of great importance with tunnel-type gates, as seen from Fig. 8. Slight changes in the ratio of the cross-sectional areas A_1 and A_2 may change the downpull considerably. Because of the limitation in accuracy with which the design can be reproduced in the field and because of the uncertainties in the determination of the discharge coefficients C_1 and C_2, it is advisable to provide for an adjustable flow passage—preferably A_1—in order that predetermined conditions can be realized on the site.

With respect to the four possible combinations of arranging top seal and skinplate [Fig. 10(c)] it is to be noted that the only possible arrangement for face-type gates and the most common for tunnel-type gates is that with seals and skin plate on the downstream side. Eqs. 37 and 38 have therefore been derived for this configuration. With the skinplate on the upstream and the top seal on the downstream side, the equations still apply, except that a buoyancy force must be added in the case of free efflux because the volume of the gate will then in general be free of water. With the top seal on the upstream side as well, only Eq. 38 becomes invalid. Since $\overline{\kappa}_T = 0$ in this case, as follows from Eq. 36, precaution has to be taken that no uplift is induced. Despite the advantage of the reduction in downpull, gates with upstream seals have only been used for relatively low heads because of a number of problems primarily resulting from the extensive vortex action in the gate slots (A27).

EXPERIMENTS

A two-dimensional tunnel-type gate [Fig. 10(a)] was tested under submerged-flow conditions in an air tunnel of the Iowa Institute of Hydraulic Research with a test section of 10-ft length and 3-ft by 3-ft cross section. The conduit height was varied by a false ceiling. Except for two test series the thickness of the model gate was chosen to be d = 2.5 in. The distribution of piezometric head along the gate lip was measured at eleven points with piezometric holes of 0.033-in. diameter, located in the bottom surface of the gate near the center line of the tunnel. The readings were taken by means of micromanometers with an accuracy of 1/1000 in. of alcohol. The reference piezometric head h was obtained from a piezometer on the downstream side of the gate lip, 0.8d above the lower edge. All measurements were performed with the gate stationary at various partial openings y and at efflux velocities V_j between 75 fps and 85 fps. The velocity head $V_j^2/2g$ was measured as the difference between the reference piezometer and a total-head tube placed in the contracted jet, about 1.25 y downstream from the lower edge of the gate and at an elevation less than 0.5 y above the floor. Traverses with a static-pressure tube verified the assumption that the piezometric heads on the downstream side of the gate and in the fully contracted section of the jet were essentially equal.

From a dimensional analysis, the distributions of piezometric head on the top and the bottom surface of the gate can both be expressed in the nondimensional functional form

$$\frac{h_T - h}{V_j^2/2g}, \frac{h_i - h}{V_j^2/2g} = \Phi' \left\{ R, F, K, \frac{x}{d}, \frac{[y(t)]}{d}, \frac{y_0}{d}, \theta, \frac{e}{d}, \frac{r}{d}, \frac{b}{d}, \frac{B}{d}, \frac{[v'(y')]}{V_j} \right\} \quad . . (40)$$

In the experiments under consideration, which were restricted to submerged flow without cavitation, the Froude number F and the cavitation K had no effect. For the condition of stationary gate positions y(t) = y = const. With the additional restriction to two-dimensional flow ($b/d \rightarrow B/d \rightarrow \infty$) the above relationship reduces to

$$\bar{\kappa}_T, \bar{\kappa}_B = \Phi \left\{ R, \frac{y}{d}, \frac{y_0}{d}, \theta, \frac{e}{d}, \frac{r}{d} \right\} \quad . . . . (41)$$

if the terms to the left of the equation are combined with x/d to yield the mean values $\bar{\kappa}$ according to Eqs. 33 and 34. The last parameter in Eq. 40, which describes the velocity profile at a distance x' upstream from the gate, is omitted in Eq. 41, because its effect has not been investigated. The specific velocity profile for which the experiments with $y_0/d = 6$ were conducted is shown in Fig. 11. It was found to be almost independent of the gate opening, the gate geometry and the Reynolds number within the range of investigation. Similar conditions prevailed for the other relative tunnel heights y_0/d.

As is apparent from Eq. 41, the experiments were confined to the investigation of $\bar{\kappa}$ as a function of the Reynolds number and five of the most influential boundary parameters interpreted in Fig. 10. Note that the face-type gate is represented in this study by large y_0/d and $y_{max} < y_0$. (Under these conditions, the effect of the corner eddy diminishes and y_0 becomes equivalent to H, see Fig. 1.)

Results.—The effect of the Reynolds number on the distribution of piezometric head along an inclined gate bottom is shown in Fig. 12 for the representative inclination $\theta = 20°$. Both Figs. 12 and 13 give evidence of local flow separation with subsequent reattachment. The flow pattern of Fig. 13 was obtained by means of a compound of oil and pigment particles which was applied to the gate surface and then subjected to the flow (A29). The zone of separation is marked by an accumulation of pigment particles, and by a region of nearly constant piezometric head followed by a sudden pressure rise, respectively.

As the Reynolds number increases, the separation zone is reduced until a critical value is reached beyond which the flow pattern and hence the distribution of piezometric head remain practically invariant. The critical Reynolds number for the conditions of Fig. 12 was found to be about 1.3×10^5. Qualitative measurements with a hot-wire anemometer indicated that this critical value marked the end of the transition to turbulence in the boundary layer immediately upstream from the onset of separation.

The effect of the Reynolds number on the downpull parameter $\bar{\kappa}_B$ is demonstrated in Fig. 14. From this diagram it becomes evident whether or not the critical Reynolds number has been reached for a particular lip shape. All subsequent experiments were conducted at Reynolds numbers around 2×10^5.

The influence of the various geometric parameters upon $\bar{\kappa}_B$ is illustrated by Figs. 15 to 18. The data for $\bar{\kappa}_B$ were obtained by graphical integration of the measured distribution of piezometric head along the bottom surface of the gate according to Eq. 33. The corresponding data for $\bar{\kappa}_T$ pertaining to the top surface of the gate follow immediately from Eq. 34. For a downstream top seal that remains in contact with the wall of the gate chamber during operation, $\bar{\kappa}_T$ was found to be almost independent of the gate geometry, as shown in Fig. 7. The evaluation of $\bar{\kappa}_T$ for other top seal arrangements has been considered in the analytical part of this paper.

The coefficient of contraction was determined by using its definition

$$C_c = \frac{Q'}{\left(b\ y\ V_j\right)} \qquad (42)$$

in which Q'/b is the rate of flow per unit width, obtained by integrating the upstream velocity profile (Fig. 11). The accuracy of this procedure diminished substantially with decreasing gate opening y. The variation of C_c with y/y_0 for some combinations of the investigated geometric parameters is represented in Fig. 22.

Analysis.—All experimental data represented in this paper are strictly valid only for submerged-flow conditions. The deviations in the $\bar{\kappa}$-terms for free efflux will presumably be small, however, unless the lip shape causes complete separation. The influence of the velocity profile upstream from the gate is conceivably of even smaller order. With regard to the Reynolds-number effect, the critical value of R was exceeded only in the investigation of the lip shapes with inclined gate bottom. For lip shapes with a projected skin plate, the Reynolds number still affected $\bar{\kappa}_B$ at the value $R = 2 \times 10^5$ at which the experiments were conducted. As evident from Fig. 14, this effect reduced to a negligible amount with increasing e^*/d and, remarkably, also for the condition of complete separation from the gate lip (lip shape No. 9).

For a given relative gate opening y/d, the ratio of the piezometric head at any point of the gate lip to the velocity head $V_j^2/2g$ decreases with decreasing angle of inclination θ of the bottom surface, with decreasing relative length of the projection of the downstream skinplate e/d, and with increasing relative conduit height y_0/d. The piezometric heads are generally larger than the reference head h downstream from the gate. The occurrence of minimum piezometric heads smaller than h, marked by $(\bar{\kappa}_B)_{min} < 0$ (see Fig. 6), is of interest with respect to the susceptibility of a lip shape to cavitation. As shown in Fig. 20, $(\kappa_B)_{min}$ is a function of the relative gate opening y/d and

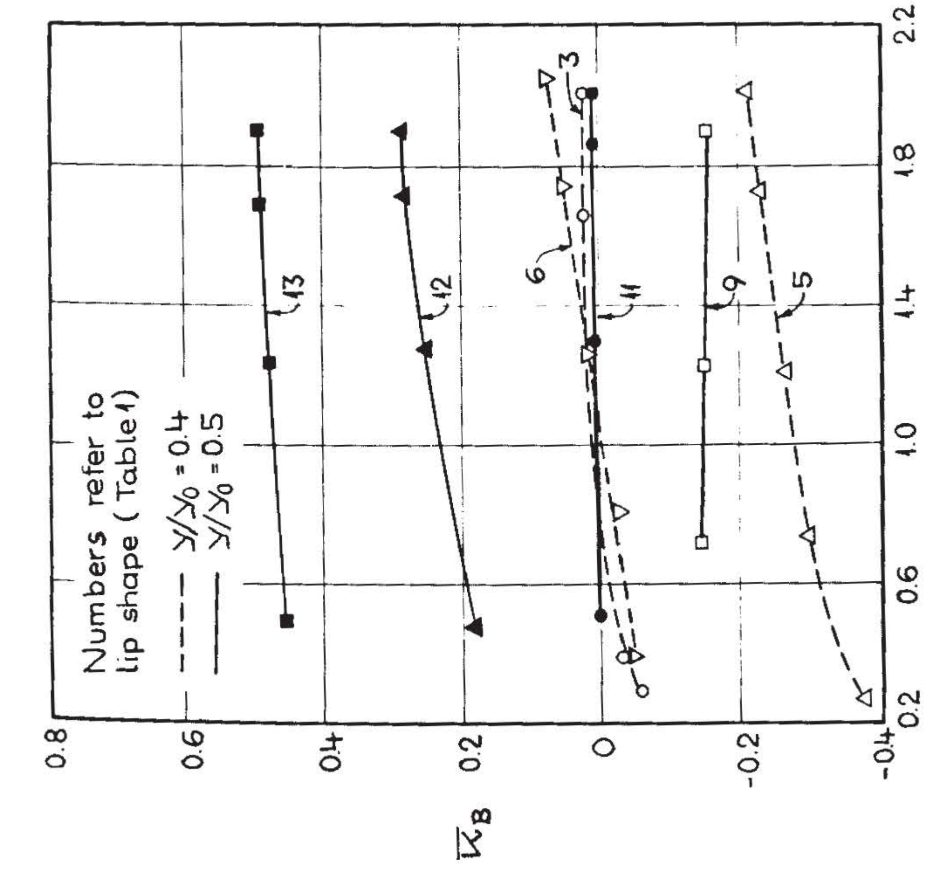

FIG. 14.—VARIATION OF $\overline{\kappa}_B$ WITH REYNOLDS NUMBER

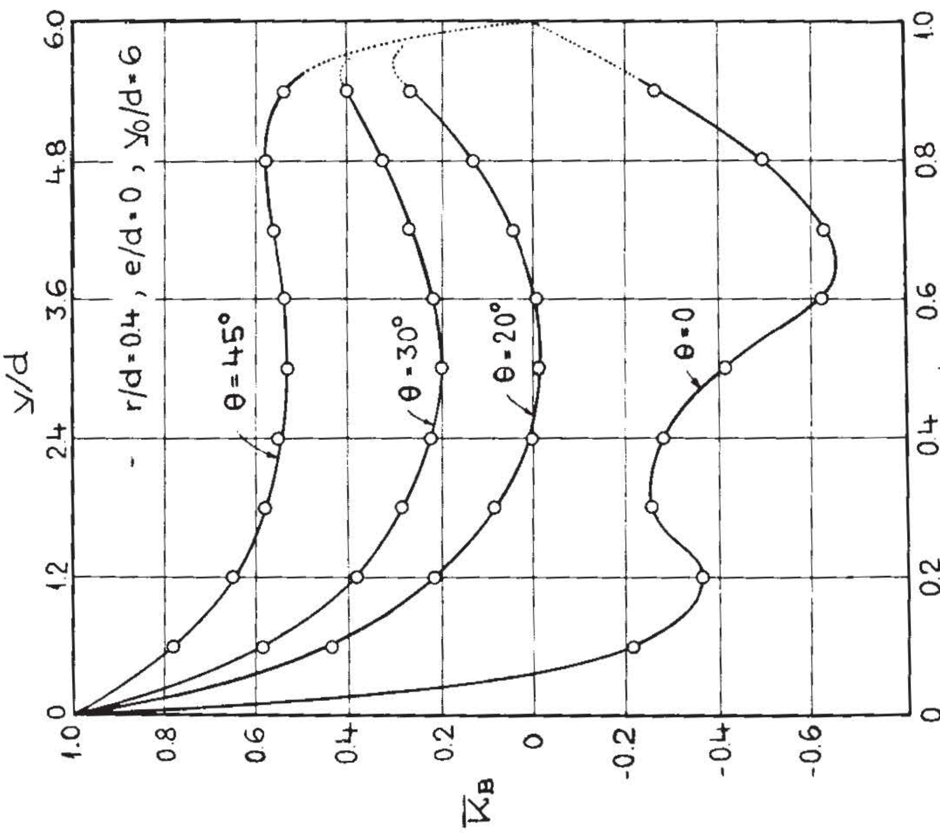

FIG. 15.—VARIATION OF κ_B WITH RELATIVE GATE OPENING FOR VARIOUS θ

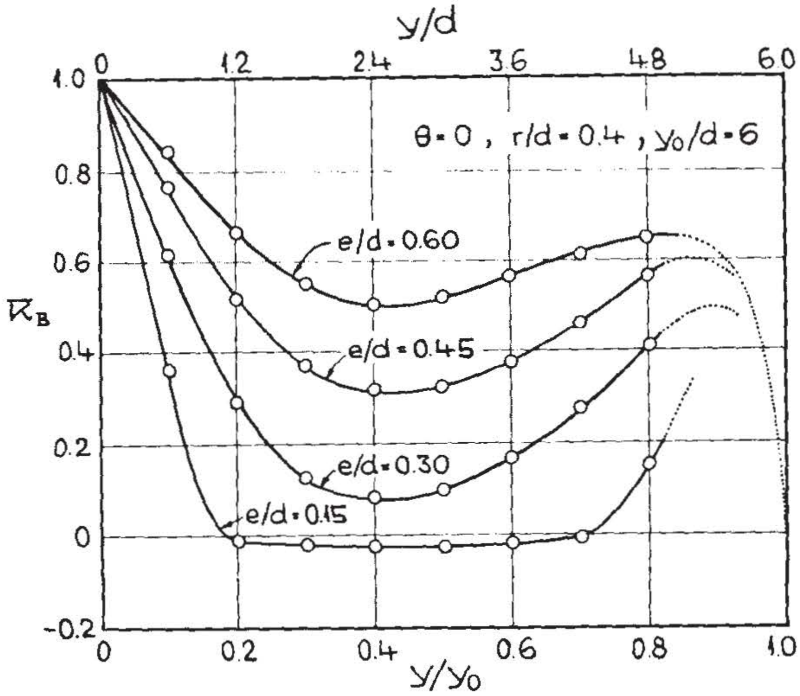

FIG. 16.—VARIATION OF κ_B WITH RELATIVE GATE OPENING FOR VARIOUS e/d

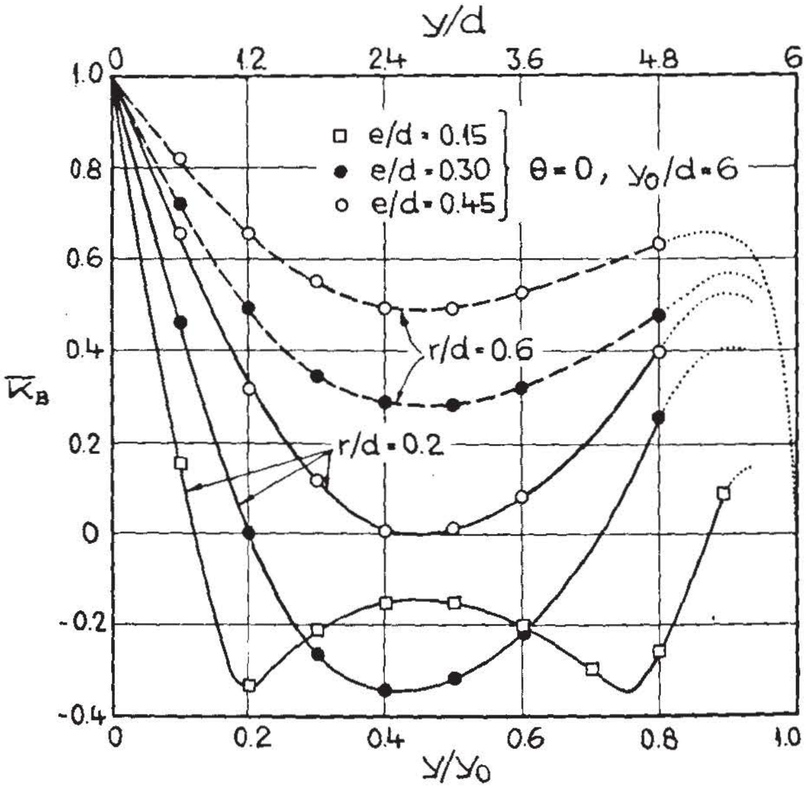

FIG. 17.—VARIATION OF κ_B WITH RELATIVE GATE OPENING FOR VARIOUS r/d

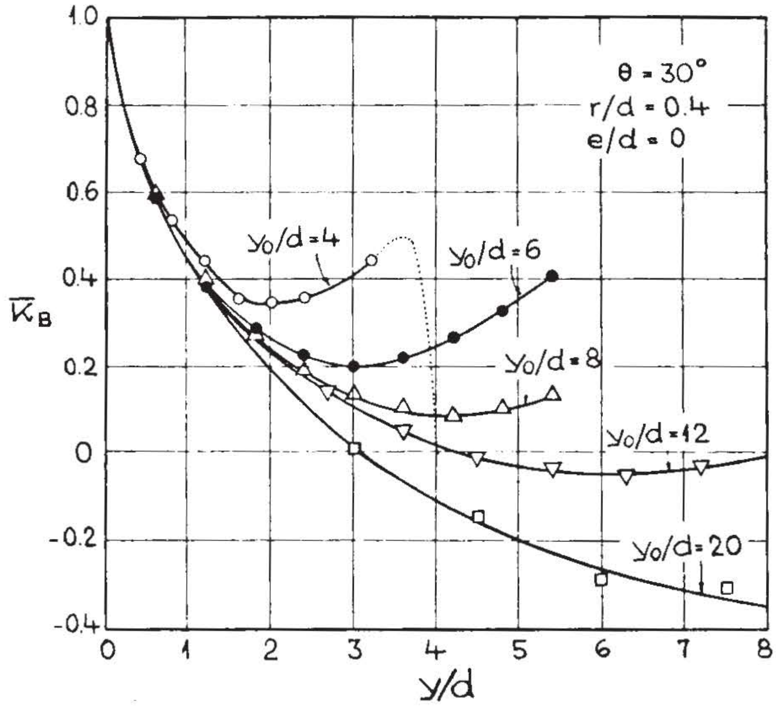

FIG. 18.—VARIATION OF κ_B WITH RELATIVE GATE OPENING FOR VARIOUS y_0/d

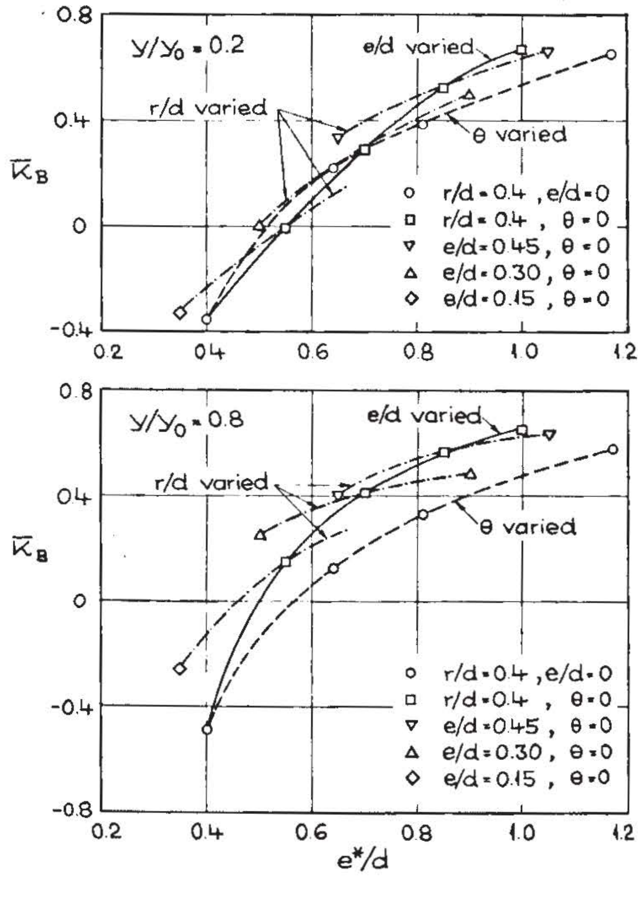

FIG. 19.—VARIATION OF κ_B WITH e^*/d FOR $y_0/d = 6$

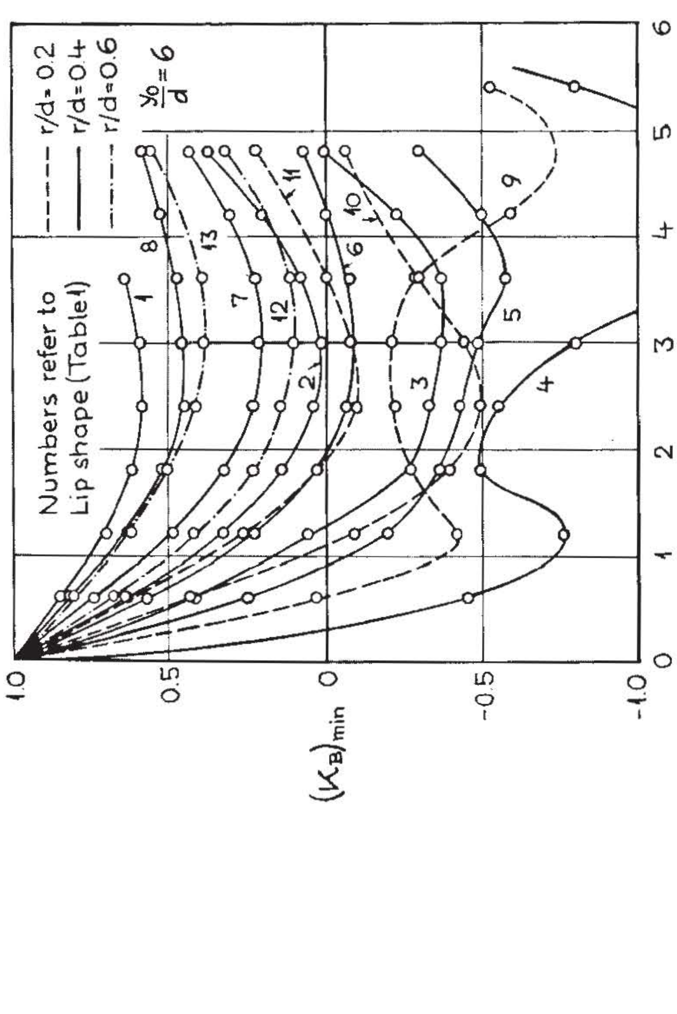

FIG. 20.—(a) VARIATION OF $(\kappa_B)_{min}$ WITH RELATIVE GATE OPENING. (b) LOCI FOR $(\kappa_B)_{min} = 0$

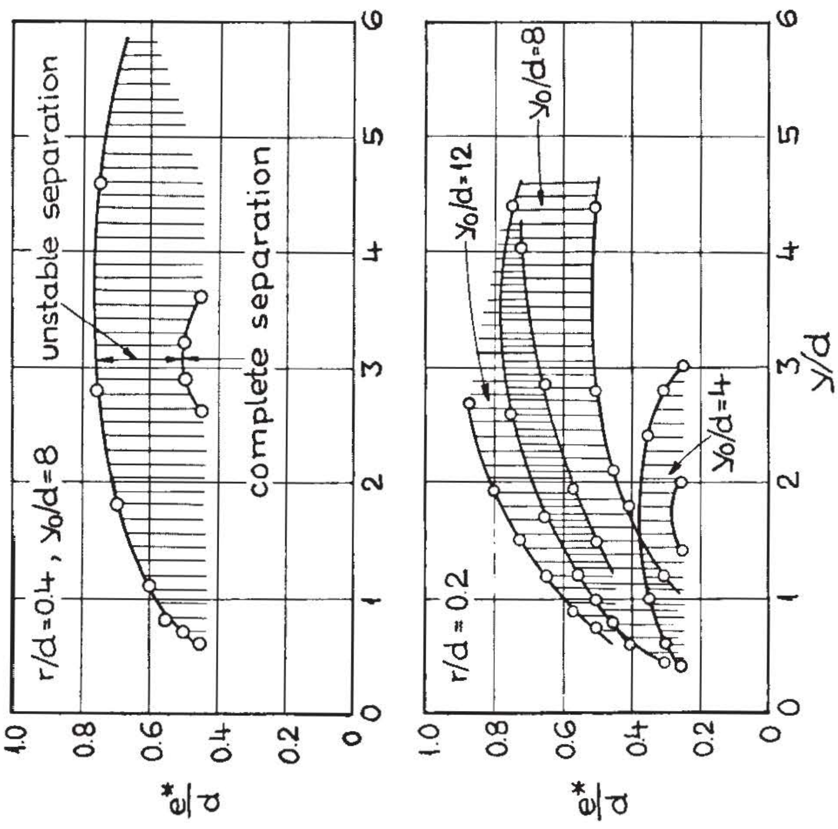

FIG. 21.—REGION OF UNSTABLE FLOW CAUSED BY THE TRANSITION TO COMPLETE SEPARATION OF FLOW FROM THE GATE LIP

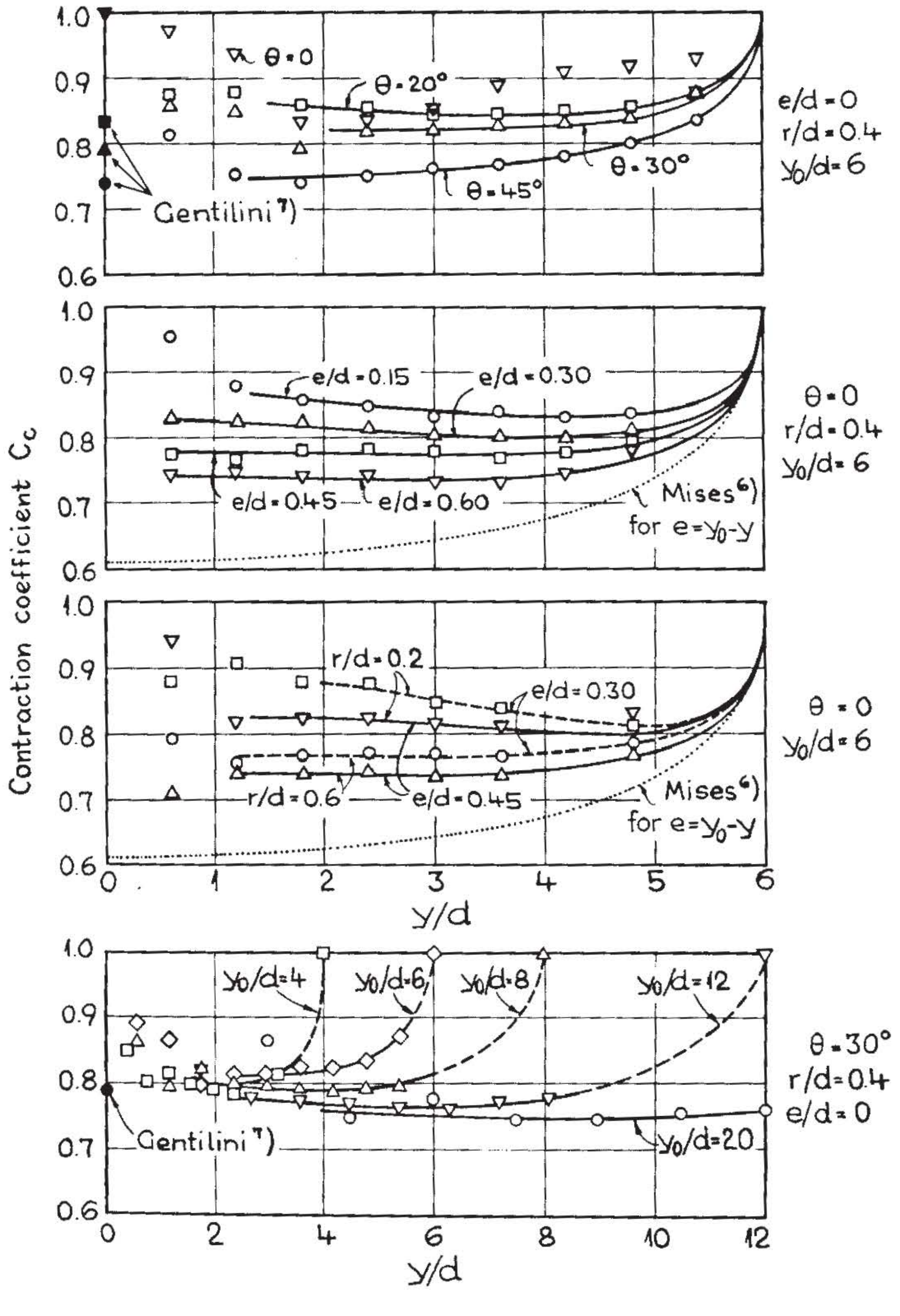

FIG. 22.—VARIATION OF C_c WITH RELATIVE GATE OPENING FOR VARIOUS θ, e/d, r/d, AND y_0/d. (SUBMERGED FLOW.)[8]

may become negative for small values of θ or e/d. The loci for the limiting condition $(\kappa_B)_{min} = 0$, when plotted with respect to e*/d and y/d, follow a continuous curve for each relative radius r/d and relative conduit height y_0/d, regardless of whether the bottom surface is inclined or followed by a projection of the skinplate. Fig. 20 can be used to determine whether subatmospheric pressures along the gate lip may develop during the gate operation for a given design parameter e*/d and a given reference head h. Piezometric heads h < 0,

[8] Gentilini, B., "Encoulement sous les vannes de fond inclinée ou à secteur," La Houille Blanche, Grenoble, France, Vol. 2, 1947, p. 145.

of interest in this respect, are generally confined to free or partially submerged efflux at small gate openings and depend in magnitude on the dimensioning of the aeration facilities. It is important to note that the diagrams of Fig. 20 refer to mean values of the actually fluctuating piezometric heads and that lower values may hence be reached instantaneously. In the case of boundary forms causing separation, moreover, cavitation is known to begin within the fine-scale eddies formed at the separation surface long before the boundary pressure attains its vapor limit.

Local separation of flow with reattachment to either the inclined bottom or to the projection of the downstream skinplate occurs for the majority of the investigated lip shapes. Separation is reduced and ultimately eliminated as the gate lip approaches either the floor or the roof of the conduit. The smaller the relative conduit height y_0/d, the less the tendency toward separation. An increase in r/d or θ also reduces separation. For $y_0/d = 4$ and $r/d = 0.4$ the flow remains completely attached to the bottom surface provided the latter is inclined at 30° or more. Extremely flat lip shapes cause the flow to separate completely from the gate lip. The regions of transition from flow that is always attached to the trailing edge of the gate lip to completely separated flow are represented in Fig. 21 in terms of e^*/d and y/d. Exceptionally high pressure fluctuations, observed at gate openings within the transition regions of this figure, suggest that completely separated and reattached flows can alternate rapidly in this range. Since it is conceivable that such pressure fluctuations might excite gate vibration, it is advisable to choose e^*/d well above the upper critical values given by Fig. 21.

From a constructional viewpoint, e^*/d should be as small as possible. To facilitate, for a predetermined e^*/d, the selection of a lip shape of minimum downpull (equivalent to maximum $\bar{\kappa}_B$), some of the data of Figs. 15 to 18 were replotted in Fig. 19 to yield $\bar{\kappa}_B$ as a function of e^*/d. Similar diagrams can be derived for other values of y/y_0. According to such diagrams, the downpull is essentially a function of the overall parameter e^*/d, regardless of the combination of the particular parameters r/d, θ, and e/d, at least within the range of investigation. For equal e^*/d, the projected skinplate is seen to be only slightly more favorable than the inclined gate bottom, and an increase in curvature r/d is slightly less effective than an increase in θ or e/d. Of course, the minimum downpull should not be the only criterion in the selection of a lip shape. The possibility of cavitation and of unstable flow conditions should be given primary consideration. If cavitation plays a role, for example, then any inclined gate bottom with a sufficient rounding, which does not cause flow separation, will be superior to a gate with skinplate projection of corresponding downpull characteristics, for reasons discussed above.

CONCLUSIONS

The analysis of the rate of flow past a high-head leaf gate involved empirical coefficients, the influence of which was proved to be small except for the contraction coefficient. The analysis of the hydraulic downpull acting on a high-head leaf gate was accomplished by treating separately the effects of flow and geometry. It was shown that the downpull for any flow condition and any boundary geometry can be determined in terms of the reference velocity head $V_j^2/2g$, which follows from the flow analysis, and in terms of nondimensional $\overline{\kappa}$-values, which were evaluated for some of the most significant boundary parameters experimentally. The details of the gate-lip geometry were found to be of minor influence as far as the mean downpull is concerned; with respect to the fluctuating downpull, however, they proved to be important. While the mean downpull depends essentially on the overall parameter e^*/d, the fluctuation about the mean is a function of each one of the specific parameters r/d, e/d, and θ. The most violent pressure fluctuations were observed near the transition to complete separation of flow from the gate lip. The conditions for this unstable flow separation as well as the conditions for the development of subatmospheric pressure along the gate lip were examined and analyzed.

It is hoped that the method of analyzing and presenting downpull data, as described in this paper, will prove useful in generalizing other experimental work as well, and that, ultimately, sufficient design information will become available to permit not only the prediction of the downpull for a given boundary geometry but also the synthesis of the composite form which would most favorably fit the requirements of a specific project.

The analysis reported herein is based on earlier investigations of the senior writer and was presented by him at the ASCE Conference at Omaha in May 1962. The experimental part of the paper represents an excerpt from two thesis projects (A29 and A30) conducted by the junior writers in partial fulfillment of the requirements for the degree of Master of Science in the Department of Mechanics and Hydraulics of the University of Iowa, Iowa City, Iowa, under the supervision of the senior writer, and was presented at the ASCE Conference at Milwaukee in May 1963. The paper was critically reviewed by Hunter Rouse, F. ASCE Director of the Iowa Institute of Hydraulic Research.

APPENDIX I.—NOTATION

The following letter symbols have been adopted for use in this paper:

A = Cross-sectional area of the conduit;

A_1 = minimum cross-sectional area between upstream face of the gate and upstream wall of the gate chamber;

A_2 = cross-sectional area of the contracted jet issuing from the gap between the downstream face of the gate and the downstream wall of the gate chamber;

A_c = cross-sectional area of the conduit at the section of downstream control [Fig. 1(a)];

A_s = area of the horizontal projection of the top seal;

a = ratio of the flow passages downstream from the gate to the cross-sectional area of the conduit (Eq. 6);

a' = ratio of the cross-sectional areas of the contracted jet issuing underneath the gate to that of the conduit (Eq. 3);

B = width of the gate (Fig. 10);

b = clear width of the conduit at the gate section (Fig. 10);

C, C_1, C_2 = discharge coefficients pertinent to the flow over the top of the gate (Eqs. 4, 24, 27 and 28);

C_0 = discharge coefficient for maximum gate opening (Eq. 14);

C_c = coefficient of contraction (Eq. 3);

C_d = discharge coefficient (Eqs. 17 and 23);

C_e = loss coefficient for entrance head-loss (Eq. 1);

C_L = loss coefficient (Eqs. 12 and 13);

D = diameter of the circular conduit;

d = gate thickness (Figs. 6 and 10);

d' = thickness of the skinplate (Fig. 10);

e = projection of the skinplate (Fig. 10);

e^* = total height of the gate lip (Fig. 10);

F = forces due to pressure (Eq. 7);

F_s = force due to boundary shear (Eq. 9);

f = Darcy-Weisbach resistance factor for the conduit;

g = gravitational acceleration;

H = total head in the reservoir (Fig. 1);

H_e = entrance head-loss (Fig. 1);

ΔH = head differential between reservoir and section of downstream control [Fig. 1(a)];

h, h^* = piezometric head in the contracted jet for submerged and free efflux, respectively (Fig. 1);

h_i = piezometric head at a point on the gate bottom (Fig. 6);

h_1 = piezometric head in section (1), downstream from the standing eddy [Fig. 1(a)];

h_c = piezometric head in the section of downstream control [Fig. 1(a)];

h_T = piezometric head on the top surface of the gate;

K = factor, compensating for departure from hydrostatic pressure distribution (Eq. 11);

L_1 = length of the standing eddy downstream from the gate (Fig. 1a);

L_2 = length from section (1) to the control section (c), (Fig. 1a);

N = parameter for the average wetted perimeter in the reach between sections (0) and (1), (Eq. 8);

P_1 = downpull resulting from the difference between the pressures acting on the top and bottom surfaces of the gate;

P_2 = downpull resulting from the pressure differential acting on the horizontal protrusions of the gate;

p_i = pressure intensity at a point on the gate bottom (Fig. 6);

Δp = difference between the pressure intensity of the air downstream from the gate and the atmospheric pressure at the reservoir, for the condition of free efflux;

Q = total rate of flow at gate opening y;

Q_{max} = total rate of flow at maximum gate opening;

Q' = rate of flow released underneath the gate;

Q'' = rate of flow released from the gate chamber through A_2;

R = hydraulic radius;

R = Reynolds number of the flow ($\mathbf{R} = 2dV_j/\nu$);

r = radius of curvature for the rounding of the gate lip (Fig. 10);

t = time;

V = mean velocity;

V_j = velocity in the contracted jet issuing from underneath the gate;

v = velocity;

y = gate opening (Fig. 1);

y_0 = conduit height immediately upstream from the gate;

y_2 = vertical distance from the datum to the contracted section of the jet issuing from above the gate;

α_1, β_1 = factors, compensating for the use of the mean velocity in section (1), (Eqs. 7 and 12);

γ = specific weight of water;

ζ = factor, compensating for the departure from hydrostatic pressure distribution (Eq. 7);

θ = angle of inclination of the bottom surface of the gate;

κ_B = dimensionless term for the piezometric head at a point of the bottom surface of the gate (Eq. 29 and Fig. 6);

$\overline{\kappa}_B, \overline{\kappa}_T$ = ratios of the mean piezometric head active on the bottom and top surface of the gate, respectively, to the reference $V_j^2/2g$ (Eqs. 30 and 31);

ν = kinematic viscosity of water; and

ρ = density of water.

APPENDIX II.—BIBLIOGRAPHY ON HIGH-HEAD GATES

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