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Subject: Flow characteristics of spillway buckets

PURPOSE

*2. The purpose of this report is to*  
~~to~~ investigate ~~the~~ bucket flow characteristics considering the radial effect of the bucket and to develop theoretical and experimental equations for the main-flow parameters.

CONCLUSIONS

1. A theoretical analysis and study of experimental data show a pronounced centrifugal effect on the action of the radial flow through a roller bucket and suggest that the flow characteristics in spillway buckets can be analyzed by use of the equations of pressure plus momentum with the addition of the centrifugal force.
2. A theoretical equation is developed to relate the bucket radius to the flow characteristics of two different flow conditions, one of which is described here as a ~~submerged~~ *non-submerged* jump-flow condition in which the roller action is similar to a hydraulic jump and the ~~of~~ *with a rise at the invert* of which is described here as a submerged jump-flow condition in which the roller action submerges the bucket. Also, a theoretical equation is derived for the energy loss in both. These equations are experimentally verified using data obtained by the USBR, Hydraulic Laboratory, within the

*backed up depth*

limits of Froude numbers up to 9 and ~~backing~~<sup>backed up</sup> factors (ratio of flow depth above the invert,  $y_g$ , to the supercritical depth at the invert,  $y_1$ ) to approximately 25. A theoretical equation is developed for the ~~backing~~<sup>backed up</sup> depth factor at the bucket invert for the submerged jump-flow condition. <sup>For the jump flow condition without submergence the</sup> This equation is also experimentally verified <sup>factor is only</sup> within these limits by applying a correction coefficient for air-entrainment.

3. Curvilinear effect on Froude number and critical depth of bucket flow is analyzed and it is shown that a correction factor must be applied to the originally defined Froude number, i.e.,  $F = \frac{v}{\sqrt{gy}}$  and it is also shown that the hydraulic jump can be formed in the bucket even though the Froude number is less than 1.

4. ~~Considerable information concerning jump~~, <sup>all</sup> Surge length, surge height, and other flow parameters <sup>are</sup> is analyzed, and it is shown that all of the flow characteristics may be expressed as functions of ~~the~~ flow parameters (Froude number, tailwater factor, submerged factor) and ~~the~~ shape parameters (abrupt factor, baffle factor, and radius factor).

5. Using the equations obtained, it is found that the energy loss in a submerged jump <sup>flow condition</sup> within a bucket is more than in the corresponding free jump on a horizontal floor, but <sup>consistently</sup> ~~constantly~~ less than that

of a corresponding <sup>non submerged</sup> ~~sweepout~~ jump-flow condition within the bucket. However, due to unstable characteristics of the <sup>the</sup> ~~sweepout~~ jump-flow condition, a slight submergence is recommended.

6. Comparison of energy dissipation capacity of various hydraulic jump basins and the lengths of these basins with that of the bucket shows that the bucket is more efficient in dissipating the energy and does so in a shorter length of structure.

#### INTRODUCTION

If an ~~initial~~ hydraulic jump depth,  $y_1$ , is to be formed at the toe of a bucket invert for a supercritical stream discharging over a spillway, the tailwater depth <sup>is</sup> should be equal to the subcritical sequent depth,  $y_4$ , given by the momentum equation. If the tailwater

depth,  $y_5$ , is less than  $y_4$ , the jump is swept out of the bucket.

This is <sup>defined as a jet</sup> ~~known as a flip bucket~~ flow condition, (Figure 1-a\*). If <sup>and the bucket is known as a flip bucket.</sup>

$y_5 = y_4$ , the hydraulic jump is on the verge of sweeping out of the

basin. This is defined <sup>hydraulic</sup> ~~here~~ as a ~~sweepout~~ jump-flow condition <sup>and the bucket will be known as a</sup>

(Figure 1-b). If, however,  $y_5$  is greater than  $y_4$ , the jump is <sup>hydraulic jump bucket in</sup>

submerged or drowned as shown in Figure 1-c; This is defined as a <sup>this report,</sup> submerged jump-flow condition <sup>and the bucket is known as a roller bucket.</sup>

Basic information concerning the characteristics of the bucket flow is published in many hydraulic and fluid mechanics books, yet the

All figures refer to figures in this appendix, only.

solution of the problem has been approached by means of hydraulic models. Therefore, it is apparent that an analytical study of bucket-flow phenomenon would be helpful to at least provide a theoretical guide for <sup>an hydraulic</sup> ~~the~~ model study.

In 1933 and 1945 bucket-flow characteristics were studied by the Bureau of Reclamation with the aid of hydraulic models for the Grand Coulee and Angostura Dam buckets.<sup>1/ 2/</sup> In 1953-1954 extensive hydraulic model tests were conducted by the Bureau of Reclamation's Hydraulic Laboratory to establish general design procedures.<sup>3/</sup> Similar studies were conducted by Lehigh University to define the general performance characteristics.<sup>4/</sup>

The radial effect on the flow through the bucket for both ~~sweepout~~ <sup>non-submerged</sup> jump-flow and submerged jump-flow conditions has not been conclusively established. No doubt the complexity of the behavior of the rolling body, including its turbulence and <sup>sucking</sup> ~~surge~~, has discouraged the earnest efforts of many investigators, and perhaps the perspective on the main issues of the problem has been obstructed by minor

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<sup>1/</sup> Jacob E. Warnock, "Spillway and Outlets for Grand Coulee Dam," Hydraulic Laboratory Report No. 103, USBR, 1935

<sup>2/</sup> "Hydraulic Model Studies on the Spillway for the Angostura Dam," Hydraulic Laboratory Report No. 192, USBR, 1946

<sup>3/</sup> G. L. Beichley and A. J. Peterka, "The Hydraulic Design of Slotted Spillway Buckets," Proc. ASCE, Vol. 85, No. Hy-10, October 1959

<sup>4/</sup> M. B. McPherson and M. H. Karr, "A Study of Bucket-Type Energy Dissipator Characteristics," Proc. ASCE Vol. 83, No. Hy-3, June 1957



inconsistencies of flow behavior. It is suspected that difficulties in the past have been experienced largely due to efforts to merge the phenomenon into complex theory, whereas, guidance by the simple fundamental laws of mechanics and application of empirical formulae based upon analyses of experimental data would have probably yielded substantial progress.

In order to gain a more rational understanding of this phenomenon, a combination of theory and experiments are used in this study.

Notation: The letter symbols adopted for use in this study are defined where they first appear and are arranged alphabetically in Appendix 1.\*

*Non-submerged*  
~~SUBMERGED~~ JUMP-FLOW CONDITION

Review of Theory

*in the analysis*  
The equations of pressure ~~plus~~ <sup>and</sup> momentum are expressions of basic theories and must be satisfied in the simultaneous algebraic calculations required for the solution of <sup>hydraulic</sup> jump problems. Recently a concept of the hydraulic horizontal jump was used for analysis of the bucket flow where an apron extended horizontally from the bucket invert.<sup>5/</sup> Centrifugal force was not taken into consideration. (This type of bucket is called a half bucket in this analysis.)

~~Further developments~~ of solid and slotted buckets have shown that *However, other studies*

<sup>5/</sup> Serge Leliavsky, "Irrigation and Hydraulic Design," Chapman and Hall, Ltd., London, Volume 1, 1955

the centrifugal effect on the pressures in the bucket (Figure 2) may become so pronounced that it must be included in <sup>an</sup> the analysis ~~of the mechanics of flow~~.

~~The sweepout~~ <sup>non-submerged</sup> jump-flow condition, <sup>as defined here,</sup> Figure 1-b, is not a recommended <sup>prototype</sup> operating condition since <sup>the jump is on the verge of sweeping out of the bucket,</sup> it ~~creates much water surface roughness~~ and is unstable, <sup>therefore,</sup> but is analyzed here only as preparation for analysis of the submerged jump-flow condition.

### Definition Sketch

Based on recent model studies 1/ 2/ 3/ 4/ 5/ <sup>the</sup> definition sketch, for the bucket flow is presented.

*How is the definition sketch based on model studies?*

Referring to Figure 1-b, the factors involved in the analysis of the <sup>non-submerged</sup> sweepout jump-flow conditions are defined as follows:

Sequent depth factor ( $\psi$ ) is defined as the ratio of the sequent depth  $y_4$  to the supercritical initial depth,  $y_1$ .

$$\psi = \frac{y_4}{y_1} \quad (1)$$

Tailwater factor ( $S_1$ ) is defined as the ratio

$$S_1 = \frac{(y_4 - y_2)}{y_2} \quad (2)$$

5/ Atsuya Okada and Takeshi Ishibashi, "Hydraulic Model Tests on Flood Spillway of Sakuma Dam," Central Research Institute, Electric Power Industry, Japan, June 1, 1956

where  $y_2$  is the subcritical sequent depth of <sup>a</sup>normal free jump on <sup>a</sup>horizontal floor.

Abrupt factor (Z) is defined as the ratio of abrupt rise, z, to initial depth,  $y_1$ ,

$$Z = \frac{z}{y_1} \quad (3)$$

Baffle factor (k) is defined as the ratio of the total width of the baffle,  $b_t$ , to ~~that of~~ <sup>the total</sup> bucket width, b,

$$k = \frac{b_t}{b} \quad (4)$$

Radius factor (R) is defined as the ratio of the initial depth,  $y_1$ , to bucket radius,  $r_1$ ,

$$R = \frac{y_1}{r_1} \quad (5)$$

For slotted bucket similar to the Angostura Spillway bucket,  
 $0 < k < 1$  and  $Z > 0$ .

For solid bucket similar to the Grand Coulee bucket without baffle,  $k = 1$  and  $Z > 0$ .

For half bucket where a <sup>horizontal</sup> apron extends horizontally from the bucket invert, <sup>both</sup> either k ~~or~~ and  $Z = 0$ .



### Drag Forces on Bucket Baffles

If the shear stress along the horizontal solid boundaries of a solid bucket between Sections 1 and 4, Figure 1-b, can be neglected and the momentum coefficients,  $\beta_1$  and  $\beta_4$ , are assumed as unity, then by use of <sup>the pressure -</sup> ~~force~~ and momentum theory,

$$\left(\frac{1}{2}\right) \gamma y_4^2 - \left(\frac{1}{2}\right) \gamma y_1 \left(y_1 + \frac{y_1 v_1^2}{g r_1}\right) + p$$

$$= \left(\frac{q \gamma}{g}\right) \left(\frac{q}{y_1} - \frac{q}{y_4}\right)$$

(6)

in which  $\gamma$  is the specific weight of water,  $q$  is the discharge per unit width of bucket,  $g$  is the acceleration due to gravity,  $\frac{y_1 v_1^2}{g r_1}$  is the static head correction factor of the bucket due to the radial flow. <sup>(centrifugal force)</sup>

$p$  is the force acting on the <sup>width of the baffle</sup> ~~baffle~~ unit of the solid bucket and can be written in the form of the basic drag equation

$$p = C_d \frac{\rho v_1^2}{2} \Delta Z$$

(7)

where  $C_d$  is the coefficient of drag,  $\rho$  is the mass density of water.

- <sup>6</sup> ~~7~~ Ven Te Chow, "Open-Channel Hydraulics," 1959 McGraw-Hill
- <sup>7</sup> ~~8~~ D. B. Gumensky, "Design of Side Walls in Chute and Spillway," Trans. ASCE Vol. 119, 1954

Introducing Equation 7 into Equation 6

$$\begin{aligned} \frac{\gamma y_4^2}{2} + Cd \cdot \frac{\rho v_1^2}{2} (\Delta Z - \frac{1}{2} \gamma y_1 \left( y_1 + \frac{y_1 v_1^2}{g y_1} \right)) \\ = \frac{\gamma}{g} \left( \frac{q}{y_1} - \frac{q}{y_4} \right) \end{aligned} \quad (8)$$

Equation 8 could be reduced to form

$$Cd = \frac{1}{F_1^2 Z} \left\{ 2 F_1^2 \left( 1 - \frac{1}{\psi} \right) - \psi^2 + (1 + F_1^2 R) \right\} \quad (9)$$

where  $F_1$  is the Froude number for the corresponding initial flow condition for the horizontal hydraulic jump, i.e.,  $F_1 = \frac{v_1}{\sqrt{g y_1}}$ .

Equation 9 is the drag coefficient relationship for solid bucket.

In the case of slotted bucket (Figure 1-c), the drag equation is written as

$$p = Cd \cdot C \cdot k \cdot \frac{\rho v_1^2}{2} (\Delta Z) \quad (10)$$

where  $Cd$  is the drag coefficient for the corresponding solid bucket with abrupt factor  $Z$ , and  $C$  is <sup>a</sup>the spacing parameter for drag coefficient of slotted bucket. Then, the momentum equation for slotted bucket could be written as

$$\frac{1}{2} \gamma y_4^2 + C \cdot k \cdot Cd \frac{\rho v_1^2}{2} \gamma y_1 \left( y_1 + \frac{y_1 v_1^2}{g r_1} \right) = \frac{q \gamma}{g} \left( \frac{q}{y_1} - \frac{q}{y_4} \right) \quad (11)$$

Evaluating  $C$  from equation (11) and simplifying

$$OK \rightarrow C = \frac{1}{k Cd F_1^2 Z} \left\{ 2 F_1^2 \left( 1 - \frac{1}{\psi} \right) - \psi^2 + 1 + F_1^2 R \right\} \quad (12)$$

Equation 11 is the general expression of pressure ~~plus~~ momentum equation for spillway bucket, and could be used in evaluating flow parameters, such as sequent depth factor, radius factor, etc.

### Experimental Studies of Drag Coefficient

Experimental data, taken by the USBR Hydraulic Laboratory from Grand Coulee,<sup>1/</sup> Angostura,<sup>2/</sup> and ~~"general performance studies"~~ <sup>slotted spillway buckets</sup><sup>3/</sup> were used in evaluating the drag coefficient of the bucket baffles.

<sup>as for slotted buckets in</sup>  
A graphical presentation of the data, using equation (9) as well as <sup>for  $k=1.0$  as a solid bucket</sup>, Plot of test data shows that the drag coefficient of the bucket baffle is <sup>primarily</sup> ~~mainly~~ controlled by dimensionless parameters;  $Z$  and  $k$ . The Best fitted curves for different <sup>values of  $k$</sup>  types of bucket are shown in Figure 3-a. From Figure 3-a, it is seen that  $Cd$  decreases as  $Z$  increases, and for values of  $Z$  larger than 2.5, the <sup>drag</sup> effect of <sup>the</sup> baffle is not significant. Therefore, for design purpose, a  $Z$  value of less than 2 is recommended.

Equation (12) was used

To evaluate spacing parameter,  $C$ ; test data from Angostura models<sup>2/</sup> was used and the derived values of  $C$  are plotted against baffle factor,  $k$ , in Figure 3-b. It is seen

that  $C$  value increases from  $C = 1.0$  at  $k = 100$  percent to maximum

of 1.60 at  $k = 0.67$  percent and then decreases to 0 at  $k = 0$ . Thus,

the drag force due to the baffles in a sloped bucket is from the viewpoint of drag force, it is found that the slotted

optimum when bucket of  $k = 0.67$  percent will give the best effect.

### Evaluation of Sequent Depth Factor

Substituting Equation 1 into Equation 11, using the equation of continuity, a cubic equation for sequent depth factor in a ~~over-pout~~ jump flow condition can be evaluated,

$$\psi^3 + \left\{ kC C_d F_1^2 Z - (1 + F^2 R) - 2F_1^2 \right\} \psi + 2F_1^2 = 0 \quad (13)$$

A mathematic solution of the sequent depth factor,  $\frac{y_2}{y_1}$ , is possible, but complicated, and usually introduces some imaginary root. This makes the analysis of flow characteristics much more complicated, yet the solution of the equation shows

$$\psi = f(F_1, R, k, \text{ and } Z) \quad (14)$$

or simply, the sequent depth factor in the ~~over-pout-jump~~ hydraulic condition ~~can be~~ shown as a function of flow parameter,  $F_1$ , and shape factors  $R$ ,

$k$ ,  $Z$ . This relationship can be used in solving for tailwater depth for hydraulic-jump flow conditions in the over-pout, for known values of  $R$ ,  $k$ , and  $Z$ , conditions.

Introducing a hydraulic jump factor  
Again a factor of

$$G = \frac{F_1}{\sqrt{1 + \frac{k C C_d F_1^2 y_1 \Delta Z - \frac{y_1^2 v_1^2}{g r_1}}{y_4^2 - y_1^2}}} \quad (15)$$

*limit case  $\Delta Z = 0$*

can be adopted into Equation 11 and simplifying

$$\psi = \frac{y_4}{y_1} = \frac{1}{2} (\sqrt{1 + 8G^2} - 1) \quad (16)$$

This is <sup>a form of the</sup> ~~the~~ general equation for <sup>a</sup> hydraulic jump and ~~from the above~~ analysis it is apparent that

$G = f(F_1, R, k \text{ and } Z)$   
 $\leftarrow$  Equation (16) can also be used to determine the tailwater depth.  
 However, a Fortran program is given in Appendix IV to simplify the computation of Equation 13 <sup>2</sup> to obtain the sequent depth and other factors.

### Evaluation of Radius Factor (R)

For <sup>a</sup> known tailwater condition, Equation 11 can be used in evaluating the radius factor, however, a tailwater factor,  $S_1$  is adopted as a ~~test~~ <sup>means</sup> of comparison, then

$$= \frac{(y_4 - y_2)}{y_2}$$

hydraulic jump condition is this top of bucket  
 hydraulic jump condition is this top of bucket



$$R = \frac{y_1}{r_1} = \frac{1}{F_1^2} \left\{ k C C_d F_1^2 Z + \psi^2 - 2F_1^2 \left( 1 - \frac{1}{\psi} \right) - 1 \right\}$$

$$= \frac{1}{F_1^2} \left\{ k C C_d F_1^2 Z + (1+S_1)^2 \phi^2 - 2F_1^2 \left( 1 - \frac{1}{(1+S_1)\phi} \right) - 1 \right\} \quad (18)$$

where  $\phi$  <sup>equals</sup> the sequent depth ratio,

$$\phi = \frac{y_2}{y_1} = \frac{1}{2} (\sqrt{1 + 8F_1^2} - 1)$$

and

$$R = f(F_1, S_1, Z, \cancel{k})$$

We identify  $\phi$  as the sequent depth ratio. <sup>it becomes</sup> a well known (19) the assumed conjugate depth - and then  $R$  can be determined on that basis. (20)

Equation 18 is the general radius factor equation for the bucket ~~flow in~~ the slotted-type bucket.

the spacing factor,  $e$ , and baffle factor,  $k$ , can be eliminated and

For the solid bucket in the sweepout jump-flow condition, Equation 18 ~~can be reduced to~~ <sup>becomes</sup>

~~$$R = \frac{1}{F_1^2} \left\{ k C C_d F_1^2 Z + \psi^2 - 2F_1^2 \left( 1 - \frac{1}{\psi} \right) - 1 \right\} \quad (21)$$~~

$$= \frac{1}{F_1^2} \left\{ C C_d F_1^2 Z + (1+S_1)^2 \phi^2 - 2F_1^2 \left( 1 - \frac{1}{(1+S_1)\phi} \right) - 1 \right\} \quad (22)$$

and can be expressed as function of  $F_1$ ,  $S_1$ , and  $Z$

$$R = f(F_1, S_1, Z)$$

(23)

If ~~either~~ <sup>and</sup> ~~Z~~ or  $K = 0$ , as for the half bucket, Equation 18 again can be reduced to

$$R = \frac{1}{F_1^2} \left[ (1 + S_1)^2 \phi^2 - 1 - 2F_1^2 \left( \frac{1}{4(1 + S_1)\phi} \right) \right] \quad (24)$$

which means that the radius factor can be expressed as ~~a function~~  
of only  $F_1$  and  $S_1$ .

$$R = f(F_1, S_1)$$

### Energy Loss

The initial energy at the toe of the jump or invert of the bucket can be written as

$$E_1 = y_1 + \frac{y_1 v_1^2}{g y_1} + \frac{v_1^2}{2g}$$

$$= y_1 + \frac{y_1^2 F_1^2}{y_1^3} + \frac{F_1^2 y_1}{2} \quad (25)$$

~~Introducing R~~ Substituting  $R = \frac{y_1}{F_1^2}$

$$\frac{E_1}{y_1} = 1 + F_1^2 R + \frac{F_1^2}{2} \quad (26)$$

The energy at the end of jump is

$$E_4 = y_4 + \frac{v_4^2}{2g} = (1 + S_1)y_2 + \frac{q^2}{2g(1+S_1)^2 y_2^2} \quad (28)$$

in which  $v_4$  is the mean velocity at the tailwater.

The energy loss  $E_L$  is given by

$$E_L = E_1 - E_4 \quad (29)$$

Substituting Equations <sup>25</sup> ~~25~~ and <sup>27</sup> ~~28~~ into Equation <sup>28</sup> ~~29~~ and simplifying,

$$\frac{E_L}{E_1} = 1 - \frac{(1+S_1)\phi - \frac{1}{2} F_1^2 / (1+S_1)^2 \phi^2}{1 + F_1^2 R + F_1^2 / 2} \quad (30)$$

that is

$$\frac{E_L}{E_1} = f(F_1, S_1, Z, k) \quad (31)$$

or either

$$\frac{E_L}{E_1} = f(F_1, R, Z, k) \quad (32)$$

and or

$$\frac{E_L}{E_1} = f(S_1, R, Z, k) \quad (33)$$

Thus for the relative loss of energy in various types of buckets, Equation <sup>29</sup>30 has been shown to be a function of Froude number ( $F_1$ ) tailwater factor ( $S_1$ ) and the bucket shape factors ( $R$ ,  $Z$ , and  $k$ ). It is apparent that the energy dissipating capacity of the bucket is much more than that of the corresponding horizontal jump. In order to ~~figure out~~ <sup>determine</sup> the efficiency of energy dissipation, an index  $n$  is used,

$$n = \frac{\left(\frac{E_L}{E_1}\right)_{b.j.}}{\left(\frac{E_L}{E_1}\right)_{f.j.}}$$

33  
(34)

where b.j. represents the bucket flow in sweepout condition and f.j.

represents the corresponding horizontal jump condition. <sup>for the same  $y_1$  and  $y_2$ .</sup> ~~All the~~

④ ~~the ratios factor, relative energy loss, and energy loss efficiency above-mentioned flow parameters can be obtained from the Fortran~~

program in Appendix <sup>3</sup>4.

### Curvilinear Effect on Froude Number and Critical Depth

The general specific energy equation at the toe of the jump or invert of the bucket can be written as

$$E = y + y \frac{v^2}{gy} + \frac{v^2}{2g} = y + \frac{q^2}{gy^3} + \frac{q^2}{2gy^2}$$

25  
(26)

The <sup>is</sup> critical state ~~of flow has been~~ defined as the state of flow at which the specific energy is minimum for a given discharge. ~~is~~ A

~~8/ Paul Boss, "Berechnung der Wasserspiegellage beim Wechsel des Fließzustandes," (Computation of Water Surface with Change of the Flow Type), Springer-Verlag, Berlin, 1919, pp 20 and 52.~~

theoretical criterion for critical flow may be developed by differentiating Equation <sup>25</sup> ~~25~~ with respect to  $y$  and noting  $q$  as a constant thus

$$\checkmark \quad \frac{dE}{dy} = 1 - \frac{q^2}{gy^3} \left( 1 + \frac{y}{r} \right) = 1 - \frac{v^2}{gy} \left( 1 + \frac{y}{r} \right) \quad \begin{matrix} 34 \\ (35) \end{matrix}$$

At the critical state of flow the specific energy is a minimum, or the depth where minimum energy occurs  $\frac{dE}{dy} = 0$ . Let  $y_{cb}$  represents the critical depth for the bucket flow, then  $y_{cb}$  must satisfy the following condition, that is

$$1 - \frac{q^2}{g y_{cb}^3} \left( 1 + \frac{y_{cb}}{r} \right) = 0 \quad \begin{matrix} 35 \\ (36) \end{matrix}$$

or

$$\checkmark \quad y_{cb}^3 - \frac{q^2}{gr} y_{cb} - \frac{q^2}{g} = 0 \quad \begin{matrix} 36 \\ (37) \end{matrix}$$

The solution of  $y_{cb}$  from Equation 36 can be obtained, but is not a matter of interest. However, the critical depth of ~~the linear~~ *a rectangular* channel,  $y_c = \sqrt[3]{\frac{q^2}{g}}$ , is introduced in Equation 36 to get a better comparison, that is

$$\checkmark \quad \frac{y_c^3}{y_{cb}^3} = \left( \frac{1}{1 + \frac{y_{cb}}{r}} \right) \quad (37)$$

Furthermore, the combined effect of gravity and curvature of bucket upon the state of flow, or Froude number for the bucket, can be defined as

$$F_b = \sqrt{\frac{v^2}{gy} \left( 1 + \frac{y}{r} \right)}$$

*Froude # of incoming flow plus forces due to centrifugal force.*

(38)

or

$$F_b = F \left( \sqrt{1 + \frac{y}{r}} \right)$$

(39)

when  $F_b = 1$ , the flow state ~~is~~ <sup>is that</sup> corresponding as defined by Equation ~~38~~ <sup>35</sup>, and the relationship between the Froude number for a rectangular ~~linear~~ channel,  $F = \frac{v}{\sqrt{gy}}$ , and ~~linear channel is~~ <sup>bucket flow is</sup>

$$F_b = F \sqrt{1 + \frac{y_{cb}}{r}} = 1$$

$$0 \leq \frac{y_{cb}}{r} \leq 1$$

where  $\frac{y_{cb}}{r}$  varies ~~0 to 1~~ <sup>0 to 1</sup>, thus for ~~the~~ critical ~~state~~ <sup>flow in</sup> of the bucket ~~flow~~, the corresponding Froude number of the ~~non-bucket~~ <sup>rectangular channel</sup>,  $F = \frac{v}{\sqrt{gy}}$ , will vary from 1 to  $\frac{1}{\sqrt{2}}$ . This means that hydraulic jump can be formed even though the corresponding Froude number,  $F = \frac{v}{\sqrt{gy}}$ , is less than 1.

#### SUBMERGED JUMP FLOW CONDITION

##### Definition Sketch:

Referring to Figure 1-c, the added factors involved in the analysis of the submerged jump-flow condition are defined

as follows:

Backed up depth factor ( $H_b$ ) is defined as the ratio of the depth of flow in the bucket above the invert,  $y_3$ , to the supercritical depth,  $y_1$ ,

$$H_b = \frac{y_3}{y_1} \quad (40)$$

Submerged factor ( $S_2$ ) is defined as the ratio

$$S_2 = \frac{(y_5 - y_4)}{y_4} \quad (41)$$

Tailwater factor ( $S_3$ ) is defined as the ratio

$$S_3 = \frac{(y_5 - y_2)}{y_2} \quad (42)$$

Surge factor ( $H_s$ ) is defined as the ratio

$$H_s = \frac{y_6}{y_5} \quad (43)$$

where  $y_6$  is the average surge peak depth.

#### Evaluation of Backed-up Depth Factor

The submerged hydraulic jump in a bucket is a system of two distinct streams; one, the principal stream occupying the lower portion

of the jump body, and the other a rotating mixture of water and air supported both in motion and position by forces imparted to it by the principal stream<sup>line</sup>. By the presentation of J. H. Douma,<sup>10/</sup> the depth of the principal stream<sup>line</sup> in a bucket invert,  $y_1$ , can be shown as a function of a dimensionless parameter,  $\frac{q}{r_1 \sqrt{2gH}}$ . (Appendix <sup>4</sup> D) Thus the radius factor,  $R$ , can be easily determined for the submerged jump-flow condition.

Then refer to Figure 1<sup>c</sup>, cut free body through bucket invert, the forces plus momentum equation can be written as:

$$\begin{aligned} \frac{1}{2} \gamma y_s^2 + k C C_d \Delta Z \frac{\rho v_1^2}{2} - \frac{1}{2} \gamma (y_3 - y_1)^2 - \frac{1}{2} \left( 2y_3 + \frac{y_1 v_1^2}{g r_1} - y_1 \right) y_1 \\ = \frac{\gamma y}{g} \left( \frac{q}{y_1} - \frac{q}{y_s} \right) \end{aligned} \quad (44)$$

Substituting the equation of continuity and simplifying,

$$H_b = \frac{y_s}{y_1} = \sqrt{\psi'^2 + k C C_d Z F_1^2 R - 2 F_1^2 \left( 1 - \frac{1}{\psi'} \right)} \quad (45)$$

$$\text{where } \psi' = \frac{y_s}{y_1} = (1 + S_2) \frac{y_4}{y_1} = (1 + S_2) (1 + S_1) \frac{y_2}{y_1}$$

$$= (1 + S_3) \frac{y_2}{y_1} = \frac{1}{2} (1 + S_1) (\sqrt{1 + 8 F_1^2} - 1) (1 + S_2) \quad (46)$$

<sup>10/</sup> Discussed by J. H. Douma, "Design of Side Walls in Chutes and Spillways," Trans. ASCE, Vol. 119, 1954



$H_b$  can be shown to be function of  $F_1$ ,  $S_2$  and shape factors,  $R$ ,  $k$ ,  $Z$ , that is

$$H_b = f(F_1, S_2, R, k, Z) \quad (47)$$

for a solid bucket

$$H_b = f(F_1, S_2, R, Z) \quad (48)$$

and for a half bucket,

$$H_b = f(F_1, S_2, R) \quad (49)$$

To simplify the computation, all flow parameters can be compared with the horizontal jump, and the third tailwater factor  $S_3$  is used in evaluation of the backup depth factor, then Equations 47 to 49 can be expressed as

$$H_b = f(F_1, S_3, R, k, Z) \quad (50)$$

Further more, the depth of the principal stream in a bucket invert,<sup>11/</sup>  $y_1$ , can be approximately determined, and backup depth selected.

In such a case, determination of radius factor,  $R$ , becomes necessary.

Then, by use of Equation 44, the radius factor,  $R$ , can be expressed as a function of  $F_1$ ,  $S_3$ ,  $H_b$  and shape factors  $k$ ,  $Z$ . That is

$$R = \frac{1}{F_1^2} \left[ \psi'^2 + k C C_d Z F_1^2 - H_b^2 - 2 F_1^2 \left( 1 - \frac{1}{\psi'} \right) \right] \quad (51)$$

<sup>11/</sup> P. M. Stepanov, "O podtoplennom pryzhke vody," *Gidrotekhnika i Melioratsiya*, Vol. X, No. 1, 1958, pp 43-53

or

$$R = f(F_1, S_3, H_b, k, Z) \quad (52)$$

When  $H_b = \frac{1}{3}(y_3 = y_1)$ , Equation 51 can be reduced to Equation 18.

This means that the sweepout condition is a special case of the submerged condition. Equation 44 can be used in evaluating drag coefficient for spillway buckets for submerged jump-flow condition.

The resulting equation is

$$C C_d = \frac{1}{\frac{1}{1.486} \frac{1}{2.7}} \left\{ F_1^2 R - \psi'^2 + H_b^2 + 2F_1^2 \left( 1 - \frac{1}{\psi'} \right) \right\} \quad (53)$$

Numerical values can be obtained from experimental data. However, due to air entraining facility of the bucket roller and unstable characteristics of water surface, it is reasonable to assume that the drag coefficient for submerged jump-flow condition will remain the same as for corresponding sweepout jump-flow condition.

In order to verify the assumption, experimental <sup>backdrop</sup> ~~backdrop~~ depth factors <sup>obtained from</sup> ~~taken by~~ the USBR hydraulic laboratory <sup>data</sup> ~~3/~~ are plotted against computed values using Equation 45 and drag coefficient values obtain from sweepout jump-flow condition. Because of air entraining facility of the bucket roller, the experimental <sup>backdrop</sup> ~~backdrop~~ factor seems to be higher than the computed value, Figure 4.

The best fit relationship, Figure 4, may be expressed as

$$H_{b(\text{exp})} = H_{b(\text{the})} + 1.5 \quad (54)$$

This correlation ~~is seen~~ <sup>appears</sup> to be good. ~~A~~ <sup>However, the</sup> correction factor of 1.5, <sup>should be</sup> added to ~~takes care of~~ the simplifications made in theoretical analysis.

Hence, the theoretical Equations 45 and 51 could be used to compute the relationship between  $R$ ,  $H_b$ ,  $F_1$ , and  $S_3$ , and a Fortran program is given in Appendix ~~5~~ <sup>5</sup> to simplify the computation; using the program, the required bucket radius for any particular flow can be obtained and the backup depth of any special flow condition can be easily predicted. ~~This information is not important in hydraulic design of buckets but also~~ <sup>an</sup> important phase in <sup>the</sup> structural <sup>al</sup> design of <sup>side</sup> the walls ~~in chutes and spillways~~.

#### Evaluation of Surge Factor

Approximate surge-height characteristics obtained <sup>from</sup> ~~by the~~ USBR <sup>data</sup> hydraulic ~~laboratory~~ <sup>are</sup> shown in Figure 5. The best fit curve shows that the equation of

$$H_s = 1.45 H_b^{1/12} \quad H_b^{-1/12} \quad (55)$$

<sup>to the data points,</sup> can be fitted. This information is helpful in setting top elevations for training walls.

#### Length of the Submerged Jump in Bucket

~~As tested by the USBR hydraulic laboratory,~~ the hydraulic behavior of the submerged bucket dissipator is manifested primarily by the formation of two rollers; one is on the surface moving counter-clockwise and is contained within the region above the curved bucket,

and the other is a ground roller making a surge moving in a clockwise direction and is situated downstream from the bucket. To find the length of the submerged jump, the bucket invert was taken as the origin, and the end of the jump was taken to be the end of the ~~surge~~ roller and surge, where the depth became equal to the tailwater depth,  $y_5$ .

If  $L_{b.s.j.}$  is the length of the submerged jump, the variation of  $L_{b.s.j.}$  with backup depth factor,  $H_b$ , ~~taken by the USBR hydraulic laboratory~~ <sup>depth</sup> is shown in Figure 6a. It was found that the theoretical backup factors could be satisfied by the linear equation

$$\frac{L_{b.s.j.}}{y_5} = 2.47 - 0.035 H_{b(\text{the.})} \quad (56)$$

with a correlation coefficient of 0.87.)

For <sup>depth</sup> experimental backup factors, the same relationship as given by Equation 54 can be adopted.

If Equation 45 is substituted into Equation 56, jump length factor,  $\frac{L_{b.s.j.}}{y_5}$  can be shown as a function of  $F_1$ ,  $S_2$ , or  $S_3$ , and shape factors  $R$ ,  $Z$ ,  $k$ . That is

$$L_{b.s.j.}/y_5 = 2.47 - 0.035 \sqrt{\psi_1^2 + kC C_n Z F_1^2 - F_1^2 R - 2F_1^2 \left(1 - \frac{1}{\psi_1}\right)} \quad (57)$$

or

$$\frac{L_{b.s.j.}}{y_s} = f(F_1, S_3, R, Z, k) \quad (58)$$

For  $H_b = 1$ , that is, when flow begins to sweepout,  $\frac{L_{b.s.j.}}{y_s}$  will be as ~~small~~ <sup>large</sup> as 2.44 and ~~after~~ <sup>for</sup>  $H_b > 1$ ,  $\frac{L_{b.s.j.}}{y_s}$  will ~~gradually~~ <sup>gradually</sup> become smaller.

~~gradually~~. A comparison of the jump lengths on the different types of energy dissipators<sup>12/</sup> shows that the bucket energy dissipators are the shortest.

#### Length of the Surge in Submerged Jump

The length from bucket invert to the average surge peak is taken as the length of the surge,  $L_s$ , and the relationship of  $\frac{L_s}{y_s}$  to  $H_b$  is shown in Figure 6-b. It was found that ~~the~~ <sup>data</sup> the best fit curve through the <sup>data</sup> points could be satisfied by the equation

$$\frac{L_s}{y_s} = 1.47 - 0.019 H_b \text{ (the.)} \quad (59)$$

with a correlation coefficient of 0.84.

Comparison of equations 56 and 59 shows that the length between average surge peak and end of jump has a variation of

$$\frac{(L_{b.s.j.} - L_s)}{y_s} = \cancel{0.019 H_b} 1 - 0.016 H_b \quad (60)$$

<sup>12/</sup> "Hydraulic Design of Stilling Basins and Other Energy Dissipators," Engineering Monographs No. 25, USBR, 1963

### Length of the Roller

Due to the bucket action, the length of the roller ~~was~~ not as pronounced as in the horizontal hydraulic jump. The relationship between the ratio of the roller length,  $L_r$ , to tailwater depth,  $y_5$ , and backup depth factor,  $H_b$ , is shown in Figure 6-c. ~~The~~ ~~relationship is not good~~ a variation of 0. to 0.4 is obtained.

### Energy Loss

Referring to Figure 1-c, the energy at the invert section of the bucket can be written as

$$E_1 = y_3 + \frac{v_1^2}{2g} + \frac{y_1 v_1^2}{g r_1} \quad (61)$$

or

$$\frac{E_1}{y_1} = H_b + \frac{F_1^2}{2} + F_1^2 R \quad (62)$$

The energy at end of jump is

$$E_5 = y_5 + \frac{v_5^2}{2g} = y_5 + \frac{F_1^2 y_1^3}{2y_5^2} \quad (63)$$

or

$$\frac{E_5}{y_1} = \frac{y_5}{y_1} + \frac{F_1^2 y_1^2}{2y_5^2} = \psi' + \frac{F_1^2}{2\psi'^2} \quad (64)$$

Then the energy loss  $E_L$  is given by

$$E_L = E_1 - E_5 \quad (65)$$

Substituting Equations 61 and 63 into Equation 65 <sup>and</sup> simplifying

$$\frac{E_L}{E_1} = 1 - \frac{\left( \psi' + \frac{F_1^2}{(2\psi')^2} \right)}{\left( H_b + \frac{F_1^2}{2} + F_1^2 R \right)} \quad (66)$$

Again it is shown that

$$\frac{E_L}{E_1} = f(F_1, S_3, R, H_b, Z, k) \quad (67)$$

and when  $H_b = 1$ , Equation 66 can be reduced to Equation 30, as stated above, similar conclusion can be made for the relationship between sweepout and submerged jump condition<sup>5</sup> in bucket flow.

Verification of Equation 66 is obtained by using experimental losses computed from data taken by the USBR hydraulic laboratory<sup>3/</sup> compared with theoretical losses<sup>3</sup> computed using Equations 45 and 66 with  $C_d$  value obtained from Figure 3. The results of the comparison are shown in Figure 7. The correlation is seen to be good.

The backedup depth factor is an element in the energy loss Equation 66, yet, <sup>at</sup> the experiment<sup>1</sup> results show that the variation due to error in

measurement of backedup depth has little effect on the relative energy loss and the relative loss curve, Figure 7 shows a better correlation than that of the backedup depth factor curve, Figure 4.

Through use of Equation 66, the energy dissipating capacity of the submerged bucket is seen to be more or less than that of the corresponding free jump on horizontal floor, depending upon the particular value of  $F_1$ ,  $S_3$  and shape factors  $R$ ,  $Z$ ,  $k$ . Again the index of relative dissipation, Equation <sup>33</sup> ~~34~~ is used for evaluation of dissipation efficiency. For any given  $F_1$ ,  $k$ ,  $Z$ , and  $S$ ,  $n$  could be more or less than unity, depending on  $R$  and  $S_3$ .

By differentiating Equation <sup>33</sup> ~~34~~ with respect to either  $S_3$ ,  $F_1$ , or  $R$ , and ~~treating~~ <sup>the</sup> the resulting equation equal to 0, then a maximum value of  $n$ , for any particular flow condition can be theoretically obtained. However, the resulting equation is a complicated function of  $F_1$ ,  $S$ ,  $R$  and shape factors  $k$ ,  $Z$ . A sample computer computation shows <sup>ed</sup> that the equation is an increasing function and becomes infinity as  $H_p$  increases.

In the preceeding consideration of the energy loss, it should ~~be~~ always be remembered that the computed energy loss in the submerged jump occurs in a length much less than that of the corresponding bucket jump in sweepout condition or free jump on a horizontal floor. Comparison of the energy dissipation capacity is <sup>Consistently</sup> ~~constantly~~ lower



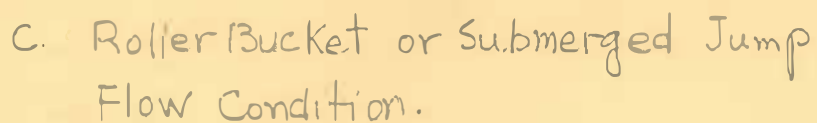
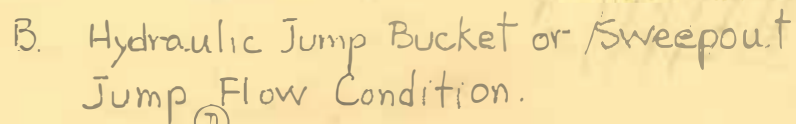
than that of the sweepout condition. From these considerations, it is concluded that the submerged jump <sup>should</sup> ~~could~~ not be preferred to the sweepout condition for energy dissipation purposes unless the <sup>depth</sup> backedup factor is less than approximately 20 percent of the tailwater depth. <sup>20/</sup> This agrees with the ~~minimum~~ tailwater recommended by USBR and the test results given by McPherson and others. <sup>13/</sup>

*Conclusion:* <sup>H</sup> ~~Here~~, the equations <sup>derived</sup> ~~mentioned~~ above can be adopted in bucket design; graphical or tabular representation of <sup>the</sup> equations is possible but due to ~~too~~ <sup>the</sup> many variables included in the analysis, and in view of the extensive and rapidly growing use of digital computers, such tables or graphs would not be of widespread interest. Instead, a Fortran program was written for use on an IBM 7090 and is shown <sup>5</sup> in Appendix ~~B~~.

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<sup>13/</sup> "Symposium on Energy Dissipators," Central Board of Irrigation and Power, Publication No. 70, New Delhi, India, August 1961

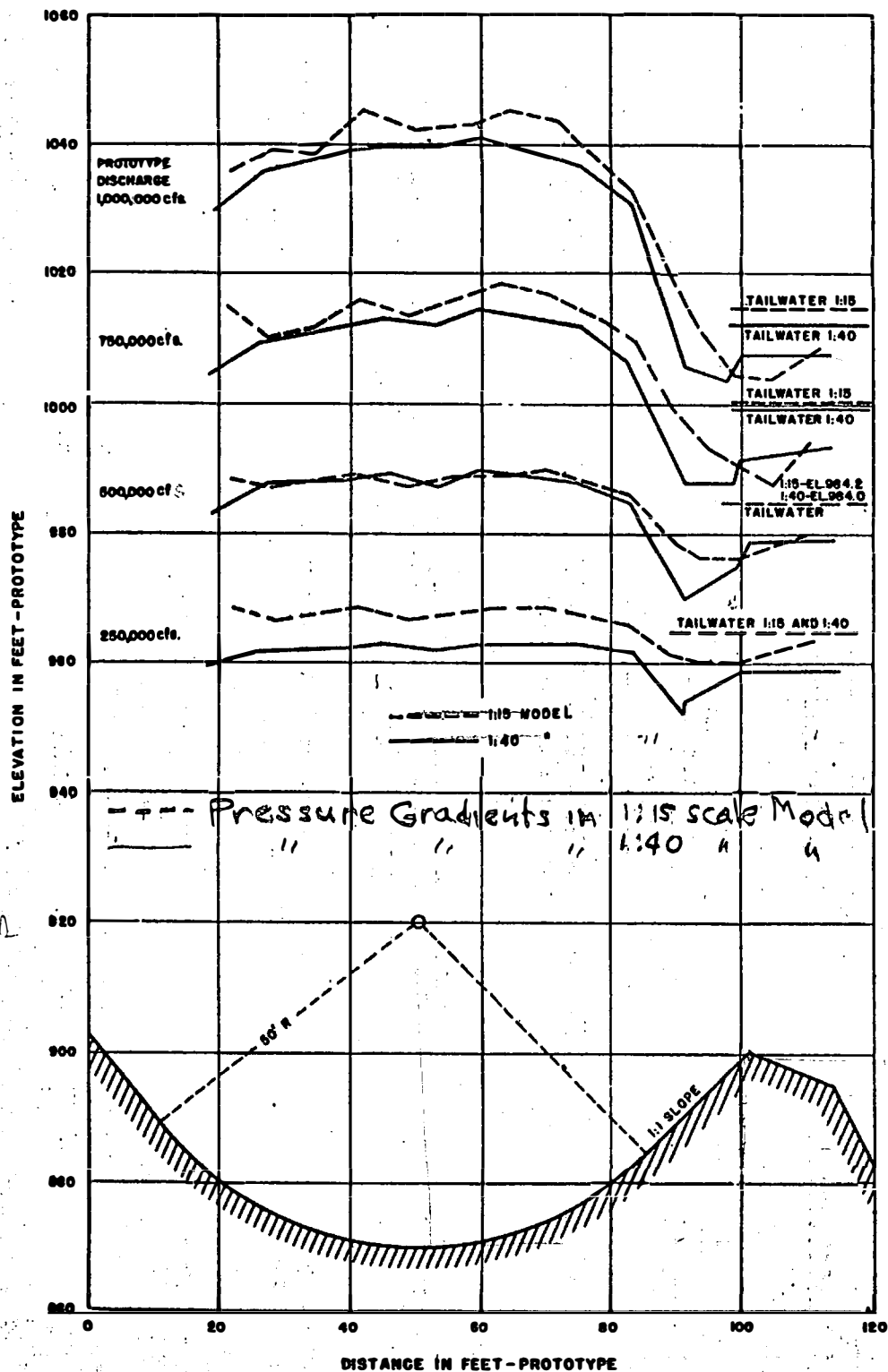
Why 2 definitions  
here for each  
condition but  
only one in  
the text?



# FLOW CHARACTERISTICS OF SPILLWAY BUCKETS

### Definition SKETCH

FIGURE 2  
REPORT HYD.

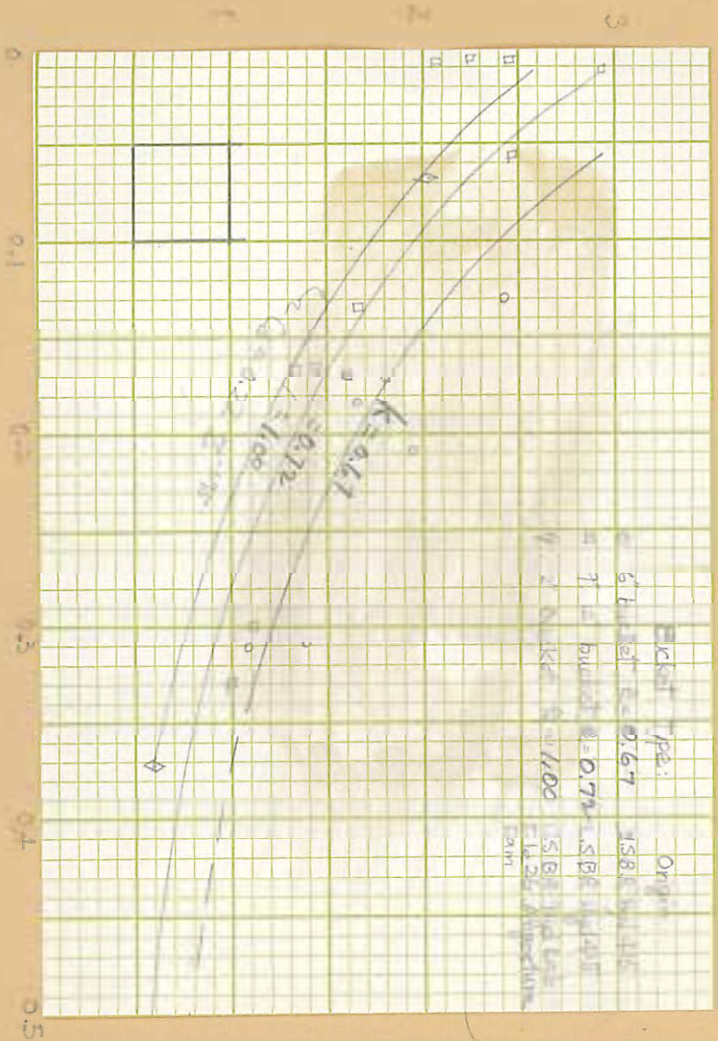


# FLOW CHARACTERISTICS OF SPILLWAY BUCKETS

Gradients  
Profile Pressure in Grand Coulee Spillway Bucket

FIGURE 3  
REPORT HYD

Abrupt Factor,  $Z_4 = \frac{Z_1}{\phi_1}$

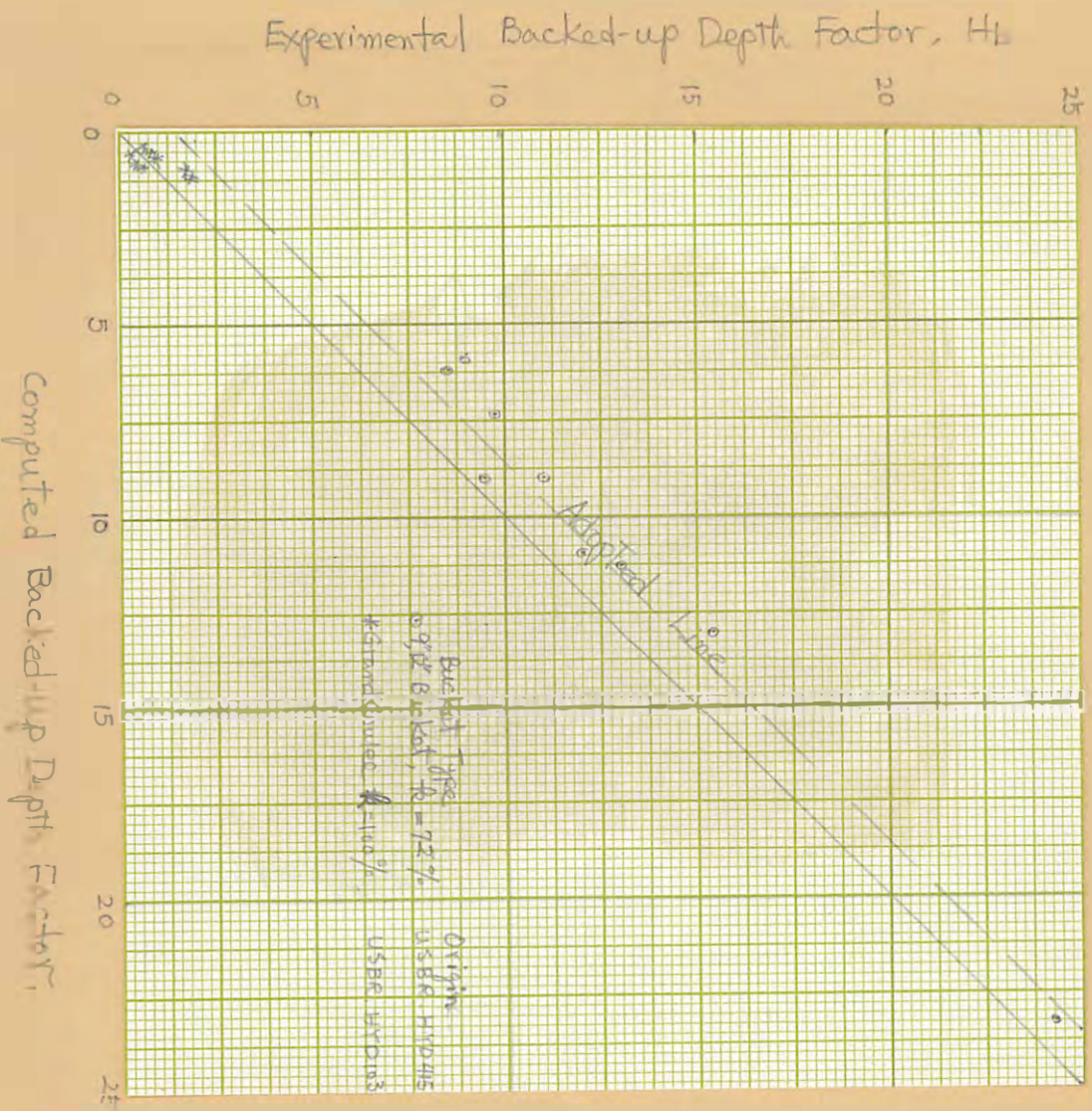


Drag Coefficient,  $C_d$

# FLOW CHARACTERISTICS OF SPILLWAYS

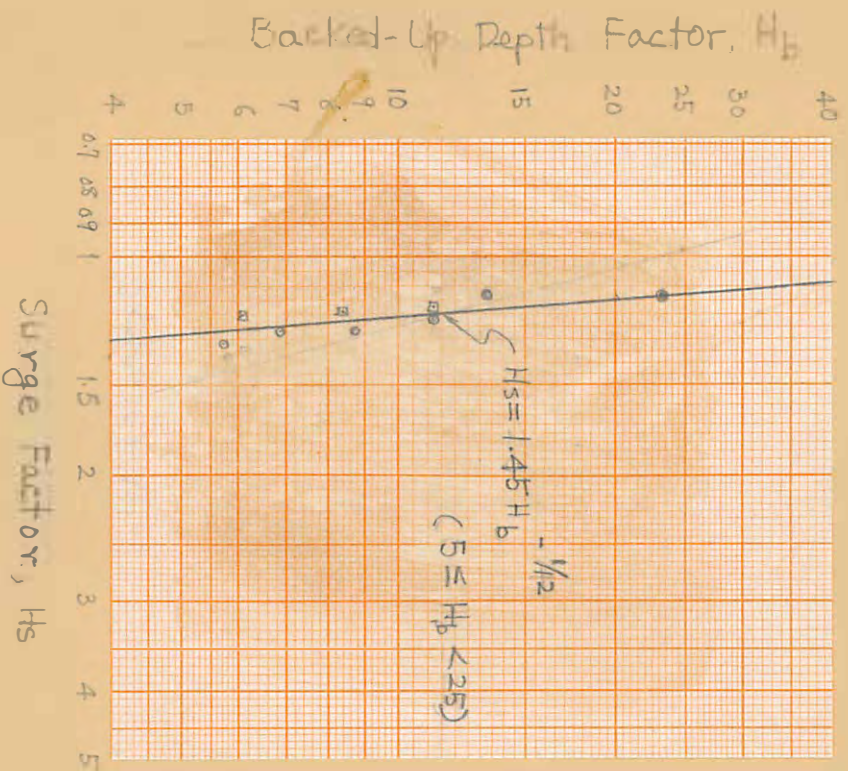
## Drug coefficients For Spillway Buckets





# FLOW CHARACTERISTICS OF SPILLWAY BUCKETS

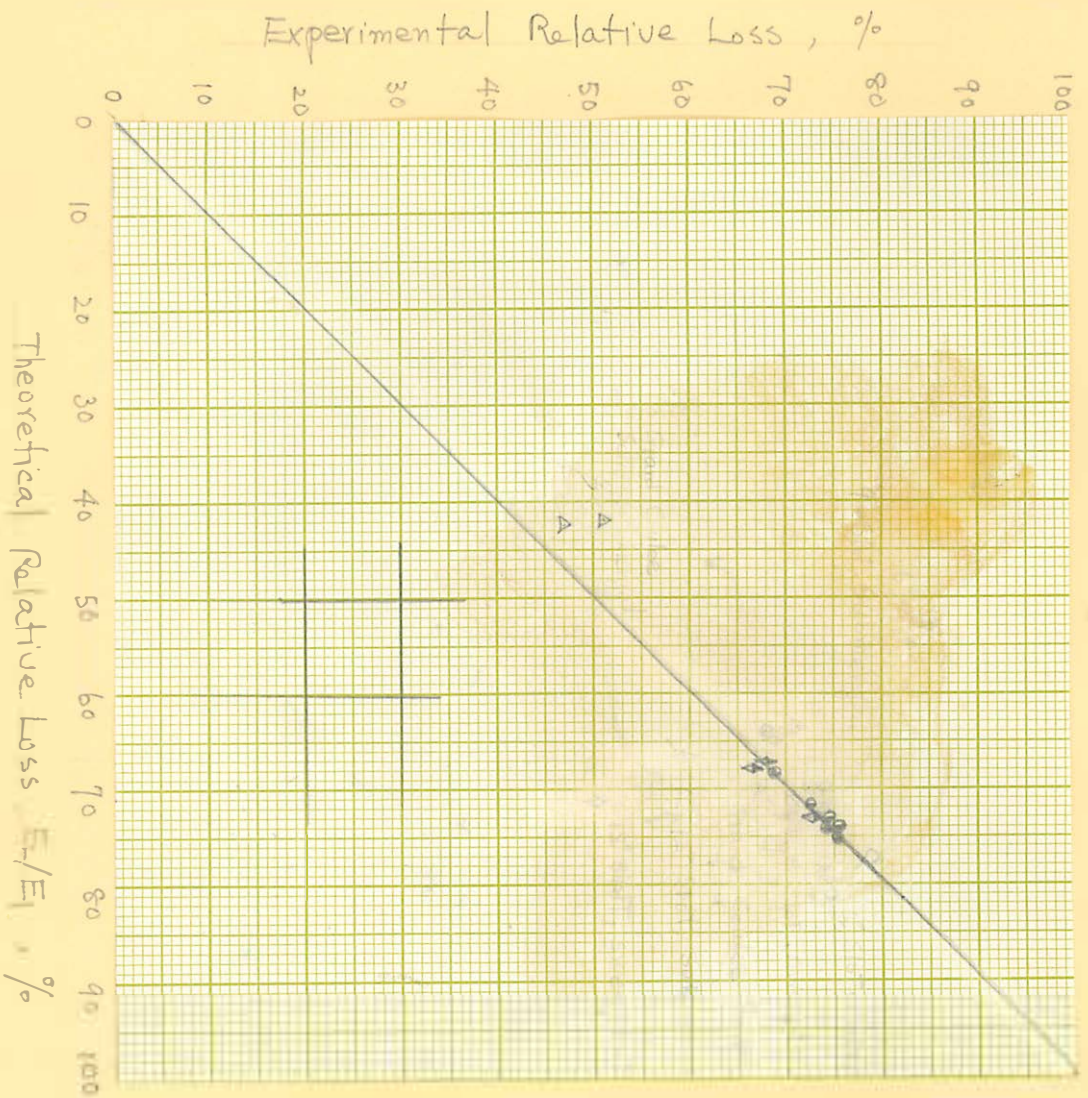
Experimental Verification of Backed-up  
Depth Factor



# FLOW CHARACTERISTICS OF SPILLWAY BUCKETS

Backedup Depth vs. Surge Depth





- 9 Slotted bucket
- ◆ 12 Slotted bucket
- ▲ Grand Coulee Solid bucket

## FLOW CHARACTERISTICS OF SPILLWAY BUCKETS

Experimental verification of Energy Loss equations for submerged jump flow condition

$q$  discharge intensity

$R$  radius factor

~~$r$  radius~~

$r_1, r_2$  radius at ~~various~~ <sup>of bucket</sup> sections

$r$   $r_2 - y_1$   
 $S$  submerged factor or tailwater factor

$S_{1,2,3}$  submerged factor or tailwater factor for various flows

$v$  mean velocity

$v_{1,2,3}$  mean velocity at ~~different~~ sections 1, 2 and 3

$x$  longitudinal distance

$y$  depth of flow

$y_c$  critical depth of linear channel

$y_{cb}$  critical depth of bucket

$y_{1,2,3}$  depth of flow at ~~different~~ sections 1, 2 and 3

$\gamma_w$  specific weight of water

$\phi$  ~~conjugate~~ sequent depth ratio for free jump

$\psi$  sequent depth factor for bucket jump

$\beta_{1,4}$  momentum coefficient

$\rho$  density of water

$Z$  abrupt factor

$z$  abrupt rise from bucket invert to top of baffle.

$(E_L/E_1)_{b.i.}$  - Energy loss in bucket flow sweep-out condition for given sequent depth factor.

$(E_L/E_1)_{f.i.}$  " " horizontal jump for given sequent depth factor

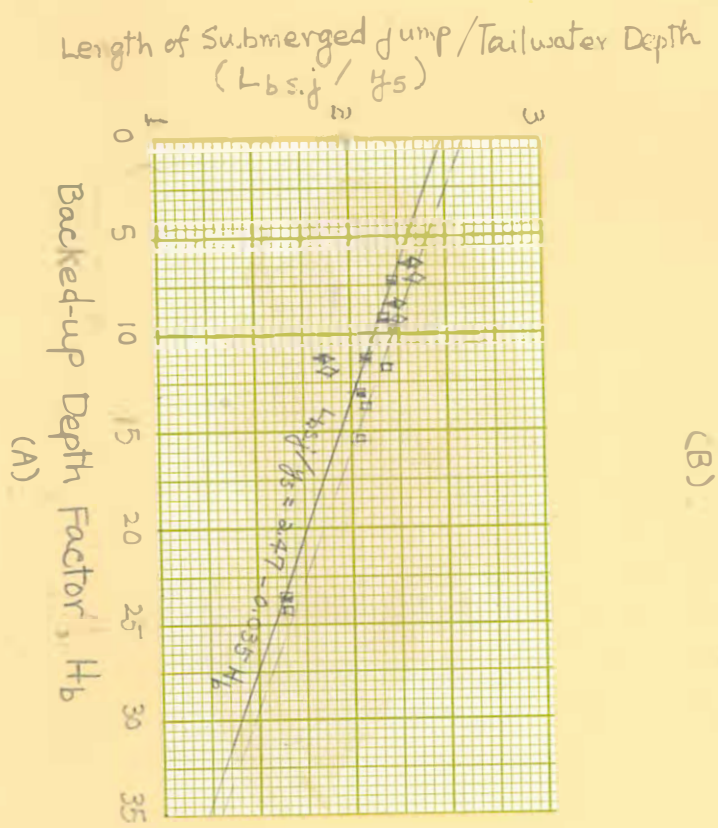
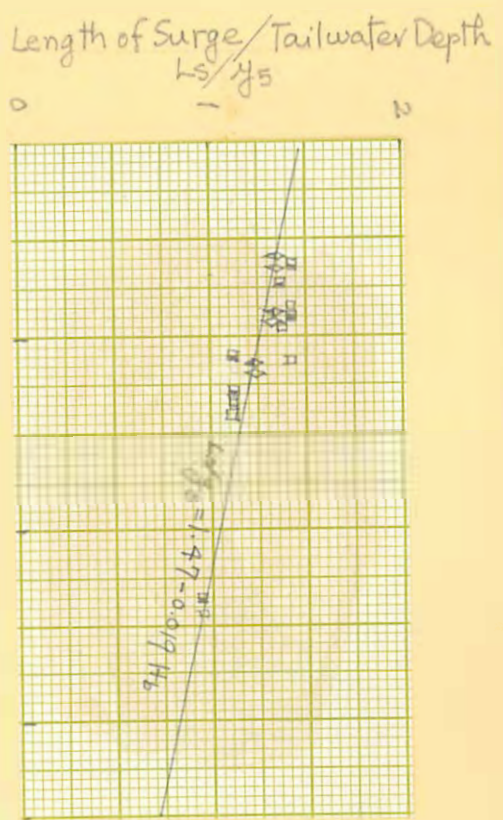
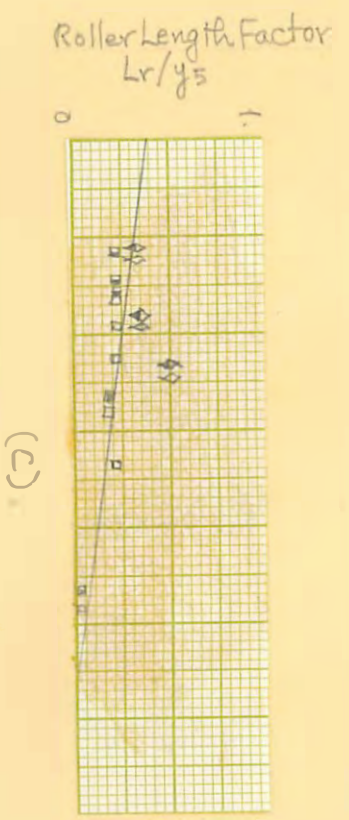


# APPENDIX 1--NOTATIONS

$b$	bucket width
$b_t$	width of baffle in bucket
$C$	spacing parameter
$C_d$	drag coefficient
$E$	specific energy
$E_1, E_2, E_3$	specific energy at <del>various</del> sections 1, 2 and 3
$E_L$	specific energy less
$F_1$	Froude number for linear channel
$F_b$	Froude number for bucket
$f$	function
$g$	acceleration due to gravity
$G$	jump constant
$H$	difference between reservoir elevation and tailwater elevation
$H_b$	backedup depth factor
$H_s$	surge factor <i>baffle factor</i>
$L_{b.s.j.}$	length of submerged jump in bucket flow
$L_r$	length of roller in bucket
$L_s$	length of surge in bucket
$n$	relative efficiency of energy dissipation
$P_r$	component of roller weight acting downstream on the principal stream of bucket
$P_d$	floor reaction
$P_u$	floor reaction

Always please

H A and C



- ◆ 12" Slotted Experimental data
- ◆ 12" Slotted, Theoretical data
- 9" Slotted, Experimental data
- 9" Slotted, Theoretical data

— Theoretical  $H_b$  Equation.  
 - - - Experimental  $H_b$  Equation.

# FLOW CHARACTERISTICS OF SPILLWAY BUCKETS

Length Parameters for Submerged Flow Condition.



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- ☐ Use color of cards as designated under "comments"

# FORTTRAN PROGRAM SHEET

PROBLEM Appendix 2. SEQUENT DEPTH FOR BUCKETS.  
 DETAIL \_\_\_\_\_  
 FEATURE \_\_\_\_\_ PROJECT \_\_\_\_\_

+ = 12 = punch

Return to \_\_\_\_\_  
(ENGR, ROOM NO., PHONE, ETC )

PROGRAMMER. Chian-Min Wu

DATE: Aug 16, 63 CHECKED:

Sheet\_ 1 of \_2\_



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- ☐ Use ----- colored cards
- ☐ Use color of cards as designated under "comments"

# FORTRAN PROGRAM SHEET

PROBLEM\_ Appendix 2

## DETAIL

## FEATURE

## PROJECT

+ = 12 - punch

- = || - punch

Job No

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(ENGR., ROOM NO., PHONE, ETC.)



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## FORTRAN PROGRAM SHEET

## FLOW PARAMETERS

## PROBLEM APPENDIX 3

RADIUS FOR SWEEPOUT BUCKET.

## DETAIL

## FEATURE

PROJECT

+ = 12 - punch

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# FORTRAN PROGRAM SHEET

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## PROBLEM APPENDIX 5 FLOW PARAMETER FOR SUBMERGED BUCKET

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## APPENDIX 4

### Determination of Depth on the Principal Stream in a Bucket Invert

According to previous model studies of flow in the spillway buckets of Grand Coulee, Pine Flat, and Popolopen Dam, J. H. Douma assumed that the velocity distribution in the bucket would be that of an irrotational vortex;  $V = \frac{A}{r}$ , in which  $A$  is a constant and  $r$  is the radius of any streamline. For this flow pattern, all the streamlines are circular and concentric with the buckets. This assumption has also been adopted for determining the depth of the principal stream in a bucket invert.

From Douma's streamline analysis, the following relationship was obtained<sup>1/</sup>

$$r_2 \log \left( \frac{r_1}{r_2} \right) = \frac{q}{\sqrt{2gH}} \quad (1)$$

where  $r_1$  is the radius of the bucket;

$r_2$  is the radius of the streamline in the principal stream of bucket;

$H$  is the difference between reservoir elevation and tail-water elevation.

Dividing both sides of Equation(1) by  $r_1$ , a dimensionless equation can be obtained, that is

$$\left( \frac{r_2}{r_1} \right) \log \left( \frac{r_1}{r_2} \right) = \frac{q}{r_1 \sqrt{2gH}} \quad (2)$$

<sup>1/</sup>Discussed by J. H. Douma, "Design of Side Walls in Chutes and Spillways," Trans. ASCE, Vol. 119, 1954



or  $\frac{r_2}{r_1}$  can be expressed as function of a dimensionless parameter

$$\frac{q}{r_1 \sqrt{2gH}} .$$

$$\left( \frac{r_2}{r_1} \right) = f \left( \frac{q}{r_1 \sqrt{2gH}} \right) \quad (3)$$

where  $r_1$ ,  $q$ ,  $H$  are all known values.

The depth of the principal stream in a bucket invert,  $y_1$ , can be expressed in terms of  $r_1$  and  $r_2$ , that is

$$y_1 = r_2 - r_1 \quad (4)$$

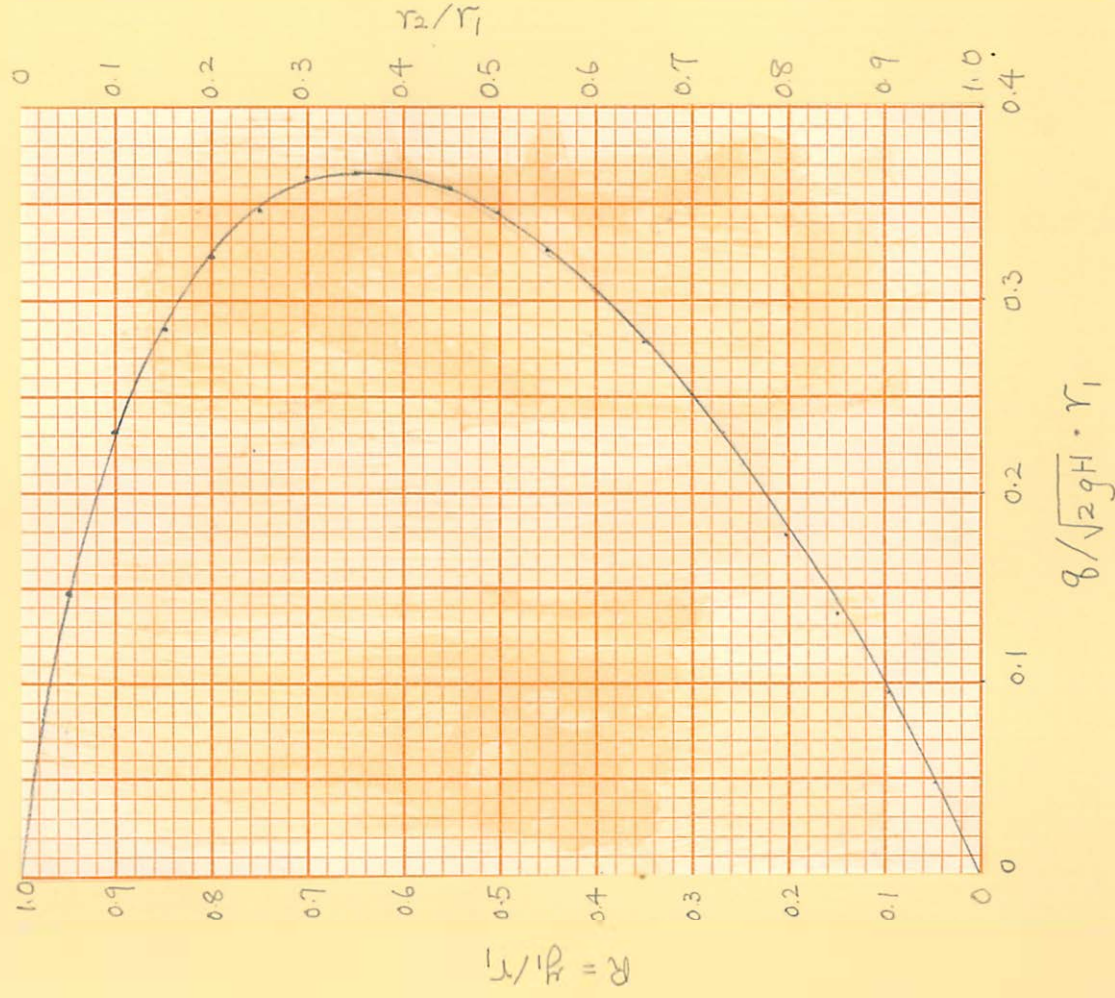
Again using a dimensionless parameter of  $\frac{y_1}{r_1}$  and in terms of  $f \left( \frac{q}{r_1 \sqrt{2gH}} \right)$ , a simple solution of  $y_1$  can be obtained by

using the relationship of

$$\left( \frac{y_1}{r_1} \right) = f \left( \frac{q}{r_1 \sqrt{2gH}} \right) \quad (5)$$

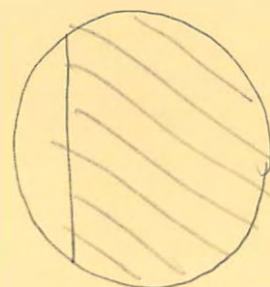
The result of Equation 5 is shown in Figure 1.

FIGURE 1.  
APPENDIX D



FLOW CHARACTERISTICS OF  
SPILLWAY BUCKETS

Radius Factor for Submerged Buckets





PROBLEM Appendix 3.

## DETAIL

## FEATURE

PROJECT

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- = 11 - punch

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(ENGR, ROOM NO, PHONE, ETC.)



# FORTRAN PROGRAM SHEET

## PROBLEM APPENDIX 5

DETAIL L \_\_\_\_

## FEATURE

PROJECT

+ = 12 - punch

- = 1) - punch

Job No. \_\_\_\_\_



Return to

(ENGR., ROOM NO., PHONE, ETC.)

# APPENDIX 1--NOTATIONS

b	bucket width
$b_t$	<i>total</i> width of baffle <sup>s</sup> in bucket
C	spacing parameter
$C_d$	drag coefficient
E	specific energy
$E_1, E_2, E_3$	specific energy at various sections 1, 2 and 3
$E_L$	specific energy less
$F_1$	Froude number for linear channel
$F_b$	Froude number for bucket
f	function
g	acceleration due to gravity
G	<del>jump constant</del> <i>hydraulic jump parameter</i>
H	difference between reservoir elevation and tailwater elevation
$H_b$	backedup depth factor $\frac{y_2}{y_1}$
$H_s$	surge factor $\frac{h_2}{h_1}$
$L_{b.s.j.}$	length of submerged jump in bucket flow
$L_r$	length of roller in bucket
$L_s$	length of surge in bucket
n	relative efficiency of energy dissipation
$P_r$	component of roller weight acting downstream on the principal stream of bucket
$P_d$	floor reaction
$P_u$	floor reaction

$q$  discharge intensity  
 $R$  radius factor  $= \frac{y_1}{R_1}$   
 $r$  radius  
 $r_1, r_2$  radius at various sections  
 $S$  submerged factor or tailwater factor  
 $S_{1,2,3}$  submerged factor or tailwater factor for various flows

$$S_1 = \frac{(y_4 - y_2)}{y_2}$$

$v$  mean velocity  
 $v_{1,2,3}$  mean velocity at different sections 1, 2 and 3

$x$  longitudinal distance

$y$  depth of flow

$y_c$  critical <sup>flow</sup> depth of linear channel

$y_{cb}$  critical <sup>flow</sup> depth of bucket

$y_{1,2,3}$  depth of flow at different sections 1, 2 and 3

$\gamma$  specific weight of water, wgt per unit volume

$\phi$  sequent depth ratio for free jump

$\psi$  sequent depth factor for bucket jump

$\beta_{1,4}$  momentum coefficient

$\rho$  density of water  $\frac{W}{g}$

$Z$  abrupt factor  $\propto \frac{y_1}{y_2}$

$z$  abrupt rise from bucket invert to top of baffle

$(\frac{E_L}{E_1})_{b.j.}$  - Energy loss in bucket flow sequent condition for given sequent depth factor.

$(\frac{E_L}{E_1})_{f.j.}$  " " " horizontal jump for given sequent depth factor

$$C_D = \frac{f}{g} \frac{w}{y_1} \left( \frac{g}{y_1} - \frac{g}{y_2} \right) = \frac{w y_2^2}{2} + \frac{w y_1}{2} (y_1 + y_2 \frac{v_1^2}{g y_1})$$

$$\frac{w}{2g} \frac{v_1 \Delta z}{y_1}$$

$$= \frac{2g \frac{w}{2g} \frac{v_1 \Delta z}{y_1}}{2g \frac{w}{2g} \frac{v_1 \Delta z}{y_1}} \left\{ v_1 y_1 \frac{w}{g} \left( v_1 - \frac{v_1}{\phi} \right) - \frac{w y_2^2}{2} + \frac{w y_1^2}{2} + \frac{w y_1^2 v_1^2}{g y_1} \right\}$$

$$= \frac{2g \frac{w}{2g} \frac{v_1 \Delta z}{y_1}}{2g \frac{w}{2g} \frac{v_1 \Delta z}{y_1}} \left\{ \frac{v_1 y_1}{g} - \frac{v_1^2 y_1}{\phi g} - \frac{y_2^2}{2} + \frac{y_1^2}{2} + \frac{v_1^2 y_1 R}{g} \right\}$$

$$= \frac{1}{2} \frac{2}{y_1} \frac{v_1^2}{y_1} \left( v_1^2 - \frac{v_1^2}{\phi} - g y_1 \psi^2 + g \frac{y_1}{2} + v_1^2 R \right)$$

$$= \frac{2}{2} \left( 1 - \frac{1}{\phi} - \frac{g y_1 \psi^2}{2 v_1^2} + \frac{1}{2} + R \right)$$

$$= \frac{1}{F_1^2} \left( 2 F_1^2 \left( 1 - \frac{1}{\phi} \right) - \psi^2 + 1 + 2 R F_1^2 \right)$$



$$= \frac{y_1}{z} - \frac{1}{\psi} - \frac{g\psi^2}{2}$$

$$- \frac{z y_1}{2} - \frac{g y_1^2}{\psi^2} + R g \frac{y_1}{2}$$

$$= y_1 - \frac{1}{\psi} - \frac{g\psi^2}{2} \left( \frac{2}{z y_1} - \frac{\psi^2}{g y_1^2} + \frac{2}{R g y_1} \right)$$

$$= \left( y_1 - \frac{1}{\psi} - \frac{g\psi^2}{2} \right) \left( \frac{2}{z y_1} - \frac{\psi^2}{g y_1} + \frac{2}{R g y_1} \right)$$

$$= y_1 - \frac{1}{\psi} - \frac{g\psi^2}{2}$$

$$y_1 \left( \frac{2}{z} - \frac{1}{\psi^2} + \frac{R g}{2} \right)$$



# CONCRETE-LINED CANALS

## FRICTION FACTORS FROM PROTOTYPE TESTS

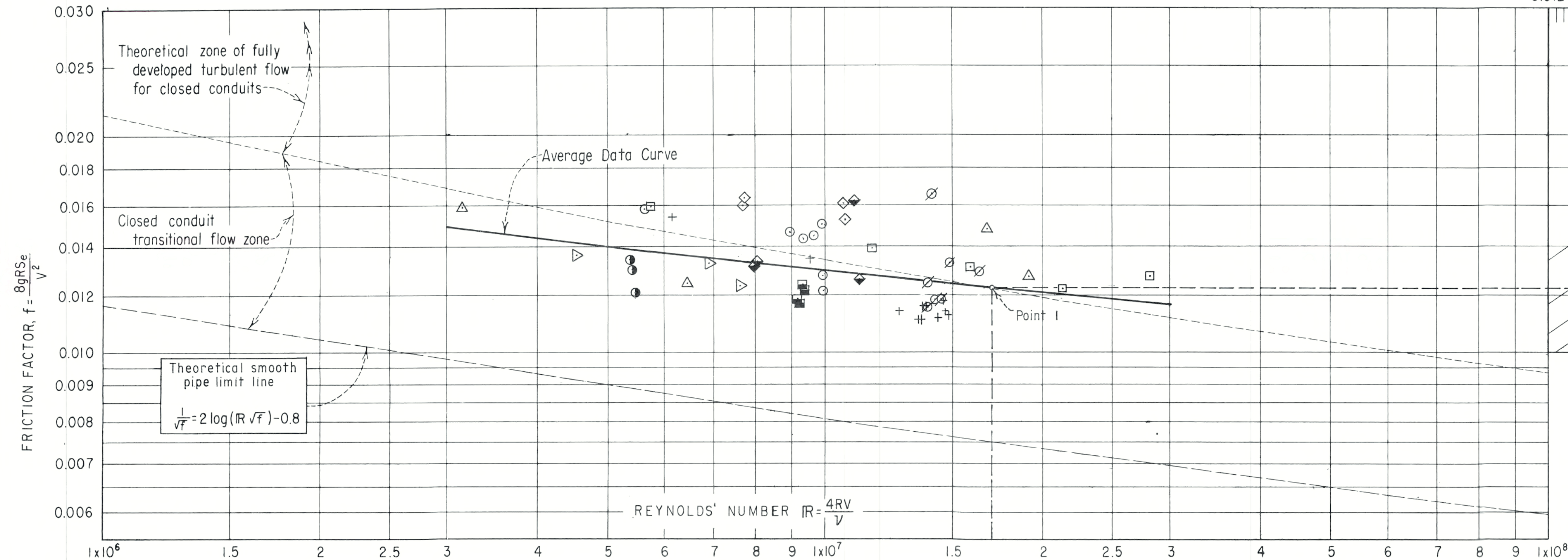


DIAGRAM 1

## ROUGHNESS COEFFICIENT "n" (For use in Manning's formula)

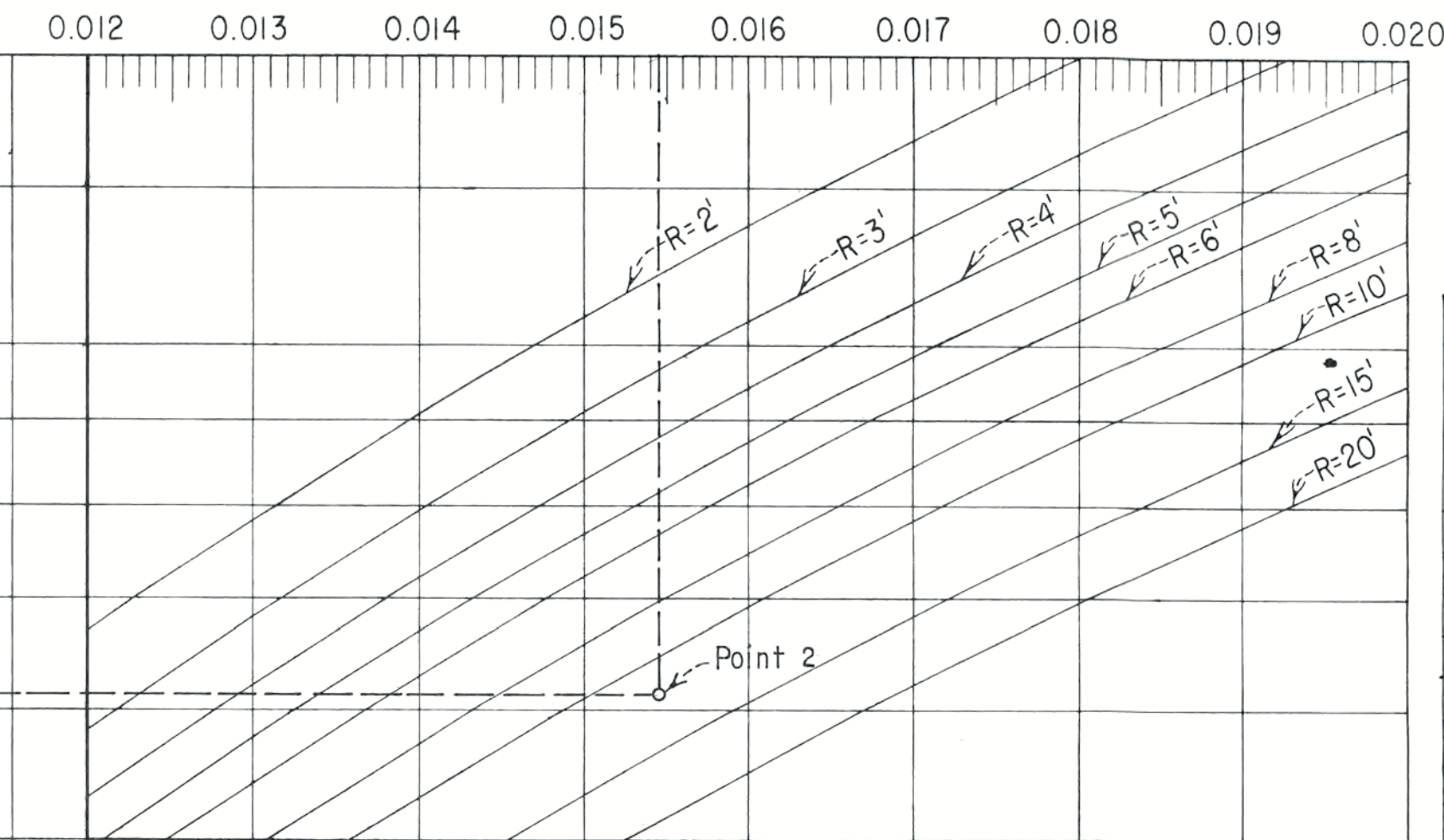


DIAGRAM 2

## PROCEDURE FOR USE

1. Determine preliminary canal section using Manning's formula and assumed "n" from Figure 5.
2. Assume water temperature which will exist at design flow and compute Reynolds' number,  $IR = 4RV/V$  for the preliminary section.
3. Enter Diagram 1 with computed value of  $IR$ , project a vertical line upward to "Average Data Curve", and mark intersection point 1.
4. Project a horizontal line from point 1 into Diagram 2 and locate point 2 at intersection with hydraulic radius line from preliminary section.
5. Project a vertical line from point 2 and read Manning's "n" from linear scale. If "n" value from Diagram 2 does not agree with assumed value, repeat steps 1 through 5 with value indicated by Diagram 2.

## EXPLANATION

$IR$  = Reynolds' number (Dimensionless)  
 $R$  = Hydraulic radius (ft.)  
 $S_e$  = Slope of energy gradient (Dimensionless)  
 $g$  = Acceleration of gravity = 32.2 ft./sec.<sup>2</sup>  
 $\nu$  = Kinematic viscosity (ft.<sup>2</sup>/sec.)  
 $V$  = Average velocity (ft./sec.)  
 $f$  = Darcy friction factor (Dimensionless)

## SOURCE OF PLOTTED TEST DATA

CANAL	SYMBOL	No. OF TESTS	CuSO <sub>4</sub> Treatment	RANGE OF TEST FLOWS (c.f.s.)
Main (Long Lake)	△	4	No	860 to 6210
Delta-Mendota	○	7	No	3370 to 4370
Main (Trail Lake)	□	5	No	1090 to 5810
East Low	▽	3	No	875 to 1980
Friant-Kern	+	11	Yes	980 to 4545
Roza Main	■	4	No	1065 to 1075
Madera	●	7	Yes	485 to 945
Gateway	●	3	No	724
C. Hansen (Reach 1)	◇	4	Yes	800 to 1290
C. Hansen (Reach 2)	◆	4	Yes	800 to 1290