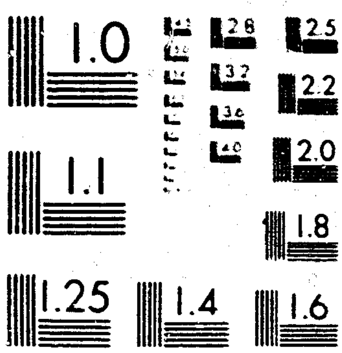
DEPARTMENT OF THE INTERIOR

MARCH 3, 1849

U.S. DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

UNITED STATES DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Engineering and Research Center
P.O. Box 25007
Building 67, Denver Federal Center
Denver, Colorado 80225



24X

GR-82-14

RAMP FLUME MODEL STUDY—PROGRESS SUMMARY

March 1983
Engineering and Research Center

U.S. Department of the Interior
Bureau of Reclamation
Division of Research
Hydraulics Branch

TECHNICAL REPORT STANDARD TITLE PAGE

GR-82-14

4. GOVERNMENT ACCESSION NO.

March 1983

Ramp Flume Model Study — Progress Summary

R. A. Dodge

GR-82-14

Bureau of Reclamation
Engineering and Research Center
Denver, Colorado 80225

Microfiche and/or hard copy available at the E&R Center, Denver, CO

A 1:3 hydraulic model was used to study small (irrigation ditch sized) ramp flumes developed by J.A. Replogle and A.J. Clemmens of ARS (Agriculture Research Service), Tempe, Ariz. The accuracy of computer calibration for the model ramp flume was found to be at least as accurate as that for Parshall flumes.

Flumes can be computer calibrated using after-construction dimension measurements. With a vertical drop at the end of the crest, the measuring device has a *submergence depth limit* of 85 percent of measuring depth above the crest. With a ramp slope 6:1 diverging from the end of the crest to the bottom of the canal, the measuring device has a 92-percent submergence depth limit. Laboratory testing results indicate that ramp flume water measuring devices have a strong potential for accurately measuring flow in canal systems.

hydraulics/ *water measurement/ hydraulic structures/ *flumes/ Parshall flumes/ critical depth/ weirs/ broad-crested weirs/ calibration/ trapezoidal flumes/ submerged flow/ ramp flume

13 1313.1

29

GR-82-14

RAMP FLUME MODEL STUDY —
PROGRESS SUMMARY

by

R.A. Dodge

Hydraulics Branch
Division of Research
Engineering and Research Center
Denver, Colorado

1982

SI METRIC

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

The research covered by this report was funded under the Bureau of Reclamation PRESS (Program Related Engineering and Scientific Studies) allocation, "USDA Ramp Flume for Discharge Measurement," DR-432. Additional funds supporting this work were furnished by the OCCS (Open and Closed Conduit Systems) committee.

ACKNOWLEDGMENTS

This ramp flume study was conducted in the Hydraulic Research Section, Hydraulics Branch, Division of Research. It was supported by the Bureau's OCCS (Open and Closed Conduit Systems) Committee and PRESS (Project Related Engineering and Scientific Studies) funds. In addition to the author, the model was operated by and data were obtained by Jim Vandeveer, Dave Dollar, and Leo Baca. Jerry Martin did concept design computations [to help designers determine dimensions for a possible ramp flume for the Charles Hansen Feeder Canal (Colorado Big Thompson Project)] and computer studies on the effects of variable changes. John Replogle provided E. James Carlson, who supervised these studies, two computer programs for obtaining calibrations. Jerry Martin modified one of the programs to output appropriate warnings when certain design criteria are violated. Final editing and preparation of the manuscript for printing were done by Richard N. Walters.

CONTENTS

TABLES

CONTENTS—Continued

FIGURES

PURPOSE

Progress achieved in this study is part of a program to gain Bureau experience with ramp flumes:

- to verify accuracy of computer calibrations,
- to verify existing design criteria,
- to develop further criteria, if needed, and
- to determine flume response to some simulated field conditions.

CONCLUSIONS

1. Comparisons of accuracy between model calibrations and computer calibrations for four different length ramp flumes indicate that computer-calibrated small-size ramp flumes are at least as accurate as Parshall flumes. Ramp flumes have a potential accuracy within 2 to 3 percent.

2. Computer programs were modified to output *limit warnings* where:

- submergence limit,
- Froude number criteria, and
- crest length criteria

have been violated, so that inexperienced users will reevaluate and provide adequate design data.

3. The main construction requirements are crests of proper length and level both in the direction of and transverse to the flow. The main calibration requirement is that all the dimensions — especially the crest width of the ramp and canal section — be measured carefully after construction. Ramp flumes can be calibrated by computer, using the after-construction dimension measurements. Thus, form movement and other construction errors can be accounted for accurately. Calibration by computer allows more tolerance during construction — saving time and cost.

4. Model data indicate that the total measuring head should be less than half the crest length so that a potential accuracy of 2 to 3 percent is obtained

5. Total head at the measuring station should be greater than one-twentieth of the crest length to assure no undulation of flow on the crest caused by frictional control. To provide sufficient measuring head relative to precision of head measurement, the measuring head should be greater than about 60 mm (0.2 ft).

6. The Froude number of the approaching canal flow should be less than 0.5 to prevent standing waves from interfering with measurements.

7. A research program should begin using the Bureau's laser-Doppler anemometer to determine velocity distribution coefficients in terms of Reynolds number and flow section shape to improve mathematical hydraulic modeling.

8. From the model having the vertical drop, at the downstream end of the crest, data indicate a *submergence limit* of about 85 percent. That agreed with the claimed submergence limit for small ramp flumes at which the actual discharge deviates -1 percent from the free flow head-discharge relationship. Therefore, the required minimum head loss was 15 percent. For the model ramp flume with 6:1 downstream diverging ramp slope, the *submergence limit* was about 92 percent.

9. Pressure measurements indicated that ramp flumes are relatively insensitive to measuring station location. A measuring station location 305 mm (12 in) upstream from the toe of the ramp is the minimum that should be allowed for 3:1 ramp flumes in small trapezoidal canals.

10. Cost estimates for a $26.3 m^3/s$ ($930 ft^3/s$) ramp flume were from 45 to 60 percent of that for an equivalent capacity Parshall flume in a retrofit situation. Investigators have cited costs for the small ramp flumes of one-tenth to one-third the cost of equivalent capacity Parshall flumes. This cost effect probably was due to more

common foundation requirements for both Parshall and ramp flumes at the large capacity sizes.

11. Because of good accuracy potential and possible cost savings, a large prototype ramp flume should be built and calibrated in the field and compared with computer calibration. During field calibration, the *submergence limit* should be determined to ascertain if there is a scale effect — similar to Parshall flumes — causing increased submergence depth limits for larger flumes.

12. Laboratory tests need to be made to determine the capability of the ramp flume to pass sediment without allowing deposits to affect or interfere with flow measurements.

INTRODUCTION

From the Water Conservation Laboratory, Agriculture Research Service, USDA (U.S. Department of Agriculture), J.A. Replogle and A.J. Clemmens developed computer programs for calibrating trapezoidal measuring flumes. Their programs account for boudary layer development and accuracies of 2 percent are claimed. The simplest type of flume consists of a ramp slope 3:1 approach up to a horizontal broad sill or crest having a vertical downstream drop back to the canal invert (see figs. 1 and 2).

Various articles by Replogle and Clemmens (see bibliography) indicate that ramp flumes are easy to install in existing canals to meet present and future water-measuring requirements for operation and conservation needs. Small (farm ditch size) ramp flumes are reported to cost one-tenth to one-third of Parshall flumes [1].[1] They have relatively small head losses and are able to tolerate higher submergences. *Submergence limits* of 85 percent for a vertical downstream crest face [2] have been

[1] Numbers in brackets refer to the **Bibliography**.

cited. The limits approach 95 percent for *long-throated* flumes. A similar increase in submergence limit was expected to occur for ramp flumes with 6:1 slopes beginning from the downstream edge of the crest. The authors cite another advantage: ramp flumes can be calibrated by computer using after-construction dimension measurements. Thus, form slipping and construction errors can be accounted for accurately which allow more construction tolerance.

Ramp flumes are reported to have no more significant problems with sediment [5] than other flume devices. For a new design and if the normal flow depth required to move the sediment is known, sufficient drop can be included to cause near normal flow both upstream and downstream of the flume. Because the flow accelerates, it is expected that most sediment carried into the approach canal (fig. 1) will go over the ramp [5].

An article by Clemmens and Replogle [1] was reproduced in [2]Bulletin No. 107. It describes some experience by the Arizona Agriculture Research Center with ramp flumes.

The Bureau's Upper Missouri Region is using ramp flumes as checks and is planning to install more. The Chief, Design Branch, Billings, Montana, contacted the Hydraulics Branch (E&R Center) and inquired about the flumes and data verifying the claimed accuracy for using ramp flumes as measuring devices. Lack of experience was the main reason for this study and investigation.

The Hydraulics Branch was provided with two computer programs by the investigators:

— BASIC program for calibrating simple trapezoidal flumes [3]

— FORTRAN program capable of calibrating complex trapezoidal flumes [6] with multiple side slopes in the approach and throat section.

[2] Water Operation and Maintenance Bulletin No. 107, Bureau of Reclamation, p. 1-8., March 1979.

BASIC PRINCIPLES

Weir Regimes and Crest Length Criteria

The ramp flume is actually a broad-crested weir having a 3:1 slope approaching the crest. Bos [7] summarizes flow regimes in terms of H_1/L_3 for a rectangular weir profile, where H_1 is total head (fig. 2) relative to crest elevation at the measuring station and L_3 is crest length. Insight into design criteria and performance limits of ramp flumes requires understanding these regimes:

When

$$H_1/L_3 < 0.08 \tag{1}$$

friction of the crest controls and undulations can occur on the crest.

When

$$0.08 \leqq H_1/L_3 \leqq 0.33 \tag{2}$$

parallel flow exists on the downstream third of the crest and the coefficient of discharge is constant over this range of H_1/L_3. Only when a weir operates between these limits, it is operating in a true broad-crested manner.

When

$$0.33 < H_1/L_3 < \text{from about } 1.5 \text{ to } 1.8 \tag{3}$$

parallel flow does not occur over the crest. Flow curvature causes increase in the coefficient of discharge, and control is near the leading edge of the crest over a separation cavity.

When

$$H_1/L_3 > \text{about } 1.5 \tag{4}$$

flow becomes unstable and, depending on corner sharpness, can spring free. At H_1/L_3 of 3 or greater, the flow acts like sharp weir flow and is stable.

These inequality relations define flow regimes. Replogle chose a criterion similar to relationship (2) to assure sufficient parallel flow so that the Bernoulli equation can be used without curvature correction in the computer programs. Replogle's [8] recommended design criterion in terms of total head H_1 at the measuring station was:

$$0.05 \leqq H_1/L_3 \leqq 0.50 \quad (5)$$

To prevent wave interference, Replogle further specified an upper limiting Froude number $V/(gD_1)^{1/2}$ of 0.5 for the approach flow.

where

g = gravitational constant (acceleration)

D_1 = hydraulic mean depth or A_1/T_1

A_1 = area of approach flow section

T_1 = top width of approach flow section

Computer Programs

Basically, the ramp flume is a critical-depth measuring device. In the computer programs, Replogle uses the relation for discharge Q at critical depth (occurring somewhere in the downstream 1/3 to 1/4 of the crest, fig. 2) for any shape channel expressed as:

$$Q = \left(\frac{gA_3^3}{\alpha_3 T_3}\right)^{1/2} \quad (6)$$

where

Q = discharge

A_3 = flow area for the entire critical depth or control location which varies with discharge

g = gravitational constant (acceleration)

α_3 = velocity distribution coefficient or kinetic energy correction factor $\Sigma(V_3^3\ \Delta A_3/\overline{V}_3^3\, A_3)$ at the control section

T_3 = top width at the control section

V_3 = velocity for an incremental flow area (ΔA_3)

$\overline{V}_3$ = average velocity for the entire control section

Replogle [6] used the energy relation, for the reach between the measuring station and critical depth location, with friction loss H_f included and expressed as (fig. 2):

$$h_2 = h_1 + \alpha_1 (Q^2 / 2gA_1^2) - A_2 / 2T_2 - H_f \qquad (7)$$

where

h_1 = measuring station head relative to crest

h_2 = control station head relative to crest

Computer routines were developed ([3] and [6]) to determine the *velocity distribution coefficient* α_2 for wide flow and friction loss during boundary layer development. The computer programs assume that α_1 is 1.04 and that design criteria relations in (5) make flow sufficiently parallel so that curvature effect is insignificant.

THE MODEL

Laboratory Flume and Measuring Techniques

Upper Missouri Region personnel use ramp flumes for checking flows up to 1.42 m^3/s (50 ft^3/s). The Bureau's Hydraulic Laboratory cannot supply this capacity so a scale model was considered. A 1:3 scale model was selected as the smallest that could be useful in checking accuracy claims of 3 percent.

Figure 1 shows the laboratory test arrangement with the 1:3 scale model ramp flume installed. The approach had about a 1:1¼ side slope, a length of about 4.9 m with a top width of 1.04 m and a depth of about 0.34 m (16- 3.4- 1.11-ft respectively). A headbox having a rock stilling and distribution baffle, and a bellmouth entrance to the canal section, was provided to smooth the approach flow. A downstream flap-type tailgate was installed to vary the submergence. The ramp and crest were poured in concrete as shown on figure 1.

Flow through the ramp flume was measured with volumetrically calibrated venturi meters. Venturi meters are an integral part of the permanent Hydraulic Laboratory facility and accurately measures discharge to within ±1 percent. The meters have a potential accuracy of ±0.5 percent.

Measuring head h_1 and submergence head h_2 were transmitted to hook gage wells by plastic tubing for more accurate measuring. The repeatability of reading water surface elevations with hook gages in the wells was ±0.3 mm (±0.012 in). Measuring head was measured 305 mm (12 in) upstream from the toe of the 3:1 ramp. Originally, the model submergence measuring station was located 1.42 m (4.67 ft) downstream of the crest and 406 mm (1.33 ft) from the flap gate. This location was considered too close to the downstream control flap gate to study submergences having a 6:1 downstream diverging ramp slope to compare with the vertical drop. Therefore, 2.44 m (8 ft) of downstream channel was added making the model submergence station 1.52 m (5.0 ft) downstream of the crest and 1.83 m (6.0 ft) from the flap gate.

Velocity measurements were made with a pitot static probe mounted on point gage vernier racks that were referenced to the ramp flume crest elevation. Pitot tube pressures were transmitted to a pressure cell connected to a digital voltage display scaled to read pitot differential directly in feet of water.

RESULTS

Test of Location for Measuring Station

Calibrations of all the different crest length ramp flumes were done with measuring stations that were 0.30 m (1 ft) upstream of the toe of the ramp. This provision is intended to keep the measuring station out of accelerating flow and/or curved water surface. Sometimes measuring stations are placed deliberately in the accelerating part of the flow; consequently, making installation of pressure taps or staff gages a critical construction measurement regarding accuracy. In doing this, one presumed advantage is that the measuring station is located within the device itself, providing better control for prefabricated devices. However, putting the measuring station in flow curvature generally makes computer calibrations more difficult. Determination of head loss and submergence limitations for "setting" crest elevations are more difficult.

To investigate the effect of water surface curvature, seven piezometer taps — including one at the measuring station — were spaced 0.15 m (0.5 ft) apart, starting from the toe of the ramp, to 0.91 m (3 ft) upstream. Water surface elevations, for five discharges ranging from 0.28 to 1.42 m^3/s (10 to 50 ft^3/s), were obtained with these taps to compare them with the measuring station values. Discharge error caused by water surface curvature or from using another location than the calibration measuring station was determined. Discharge error for the tap at the ramp toe ranged from -1¾ to -5 and averaged about -3 percent. At 0.15 m (0.5 ft) from the toe, discharge error ranged from +1¼ to -2 and averaged about -0.4 percent. The discharge errors for all the remaining upstream taps other than the measuring station — for discharges greater than 0.28 m^3/s (10 ft^3/s) — were within ±0.7 percent. For some unknown reason, error at 0.28 m^3/s was -2.0 percent for taps 0.46 and 0.90 m (1.5 and 3 ft) upstream of the toe. Variation between piezometer tap geometry probably contributed to these results to some extent. The percent error of discharge from using heads other than the head measured at the measuring station (for all the discharges and piezometer locations) is given in table 1. Based on these results, placing the measuring stations 0.30 m (1 ft) upstream of the toe of the ramp is considered generally adequate for small ramp flumes.

As a further precaution, the range of flow — where the approach length (the measuring station distance plus the ramp length) is greater than five measuring heads — should be minimized. Maintaining this approach length criterion maximizes the flow range which matches the computer assumption that contraction and roughness determines the computer calibration exclusively. However, measurements made when the approach length is greater than five measuring heads are not necessarily wrong but should be infrequent.

Model to Computer Calibration Comparison

Laboratory calibrations for 0.46-, 0.91-, 1.08-, and 1.6-m (1.5-, 3.0-, 3.53-, and 5.25-ft) crest lengths for a crest height of about 0.30 m (1 ft) are plotted with circle symbols on figures 3 through 6, respectively. Curves were fitted by eye through model data. Computer calibrations were made and are triangle symbols on the same plots. Log-log least squares curve fits also were made with the model data of discharge versus measuring head. The values of percent difference between least squares fit computed and model values of discharge were not as small as the author expected. Maximum differences are given in table 2 along with the coefficient A and the exponent n for the equation:

$$Q = Ah^{n} \tag{8}$$

where Q is the discharge and h_1 is the measuring head. Values for these equations are indicated as squares on figures 3 through 6.

Table 3 summarizes comparisons between model and computer calibrations. Column 1 lists the crest lengths. Column 2 gives the percent deviation of model from computer calibration at the head of 0.27 m (0.9 ft). Column 3 gives percent deviation at the maximum discharge at a measuring head h_1 equal to one-half the crest length. Column 4 gives the maximum percent deviation of the model data about the curve (eye) fit of the model data. Columns 5 and 6 list maximum discharge and measuring head determined on the basis of equation 5. Table 3 shows that the computer program generally determines calibrations that were always less in discharge for given mesuring heads than measured flows in the model. All model data in table 3 were within +4 percent (column 3) of the laboratory calibration which is accurate to ±1.0 percent. Therefore, it was concluded that the computer program is potentially accurate to −2 to −3 percent for small ramp flumes.

Although the computer programs produced calibrations of sufficient accuracy, deviations were consistently one sided. For given measuring heads, the computer programs generally predicted lower discharges compared to those measured in the model. This could be due to the combined results of one or more of the approximate equations and assumptions of how velocity distribution coefficient α and friction loss H_f vary with shape and hydraulic parameters. With a laser-Doppler anemometer (available in the laboratory) the Bureau should begin a research program to quantify the velocity distribution coefficient α in terms of Reynolds number and shape for flow sections. Better capability of selecting proper α values would be of considerable help to mathematical modelers in solving hydraulic problems.

Submergence Tests

The *submergence depth limit* percentage (fig. 2) can be defined as the value of $(h_s/h_1) \times 100$ where the actual discharge is 1 percent higher than the discharge computed from the free-flow relationship. This definition was used for this study. Subtracting this value of *submergence depth limit* percentage from 100 is the *minimum* required percent of water depth change required to deliver water without having submergence interfere significantly with the accuracy of flow measurement. Other investigators and the computer program use total head (fig. 2) to determine total head submergence limits $(H_s/H_1) \times 100$. *Total head submergence limits* are generally 1 to 1.5 percent greater than *submergence depth limits* $(h_s/h_1) \times 100$.

To study submergence, the 1.08-m (3.53-ft) crest length ramp flume was used. Three different discharges were set and held constant by laboratory venturi meters and valves. Submergence was varied by the downstream flap gate. The results for 0.67 m^3/s (23.6 ft^3/s) are plotted on figure 7. This plot and the data for the other two discharges indicate that the *submergence depth limit* is at about 85 percent and that discharge measurement is extremely sensitive to error just beyond the submergence depth limit. Visual determination of whether submergence exists is difficult to observe near the limit. It requires actual experience of having seen flow near the limit.

Figure 8a shows flow conditions when the ramp flume is definitely operating in the free-flow mode or with submergence depth less than 85 percent. The wave or roller generally is transverse to the downstream canal. Figure 8b shows the flow conditions when the submergence depth is just at the 85-percent limit. The straight portion of the wave persists in the center of the flow, but at the side slopes the wave forms unstable diagonal disturbance lines oscillating from just downstream of, and to the end of, the sill drop. Figure 8c shows definite submergence with the disturbance lines at the side slope starting over the downstream one-fourth of the sill crest. Figure 9 shows sketches for the same conditions shown on figure 8.

A 6:1 downstream diverging ramp was added to the ramp flume to determine how much the submergence depth limit increased. Measuring heads versus percent submergence at three different constant discharges covering the device range resulted in a submergence limit of 92 percent.

Parshall flume experience indicates that as Parshall flumes get larger, they have increasing submergence depth limits. This may be due to the location of the downstream measuring station or scale effect. This possible scale effect should be checked on large ramp flumes in the field.

Although correction procedures and submerged calibrations frequently are provided for flow measuring devices, generally it is not considered good practice to use flume-type measuring devices under submerged conditions. Any technique that provides for submergence correction increasingly sacrifices accuracy as submergence increases.

Designing a device that is to be submerged throughout all or part of its flow range requires using a calibration related to a measuring head differential. Having a second downstream measuring head station doubles the chance of wrong readings. Submerged discharge ratings are related to small differences of measuring heads. Small imprecisions of water surface elevation measurement cause large errors. As submergence becomes greater, the measuring head differentials become smaller and the differential approaches values that are about the same magnitude as for minor variations of hydraulic form and friction loss. Thus, corrections for submergence can be quite inaccurate.

A device designed for submergence is sensitive to change of downstream flow conditions. Users can temporarily dam the ditch downstream of a measuring device and then remove the obstruction after the irrigation operator has set a flow and gain considerably more than their fair share of water.

Knowledge of *required minimum head loss* is needed to design a ramp flume for a particular site or case. Because of this and the above reasons, consideration of submergence in this study is directed mainly toward determining the *submergence depth limits* for ramp flumes rather than attempting to provide submergence correction data.

Water Surface Profiles

Measured water surface elevations versus distances in the direction of flow are plotted on figure 10 for discharges of about 1.4-, 0.57-, 0.28-, and 0.14-m^3/s (50-, 20-, 10-, and 5-ft^3/s). Although water surfaces are curved throughout this range of discharge, the assumption of parallel flow for computing *measuring heads* is apparently close enough to produce computer calibration discharges that are within -2 to -3 percent. Figure 10 profile, for discharges less than 0.03 m^3/s (1 ft^3/s), is strictly schematic and shows undulating flow that can occur when friction controls crest flow. The ramp flume will not function as a measuring device in this case.

Velocity Distribution Coefficient

Velocity data were recorded on the downstream third point of the crest (fig. 2) to calculate velocity distribution coefficient α for a discharge of 0.34 m^3/s (12.2 ft^3/s) for 5 vertical profiles:

— for 5 velocity area zones, α was 1.129

— for 11 verticals and 9 zones, α was 1.094

— for 11 verticals and 10 zones, α was 1.065.

The computer program computed 1.013 for that same discharge. The difference between the computer and measured α does not explain the one-sidedness of the difference between model calibration and computer calibration discussed previously because larger values of computer α would increase the difference. Further study of velocity distribution coefficients should be made in an effort to determine the cause or causes for the one-sidedness. Possible causes are the computer routines for the α coefficients, friction, and modeling assumptions.

Demonstrations and Cost Analyses

The ramp flume was demonstrated for water measurement sessions at three Bureau Water Mangement Workshops. About 25 percent of the participants requested copies of any written reports generated by the studies. Denver Office staff requested dimensions for some larger proposed ramp flumes from 5.66 to 26.3 m^3/s (200 to 930 ft^3/s) for design studies. In 1981 a design study was made for the Charles Hansen Feeder Canal comparing costs of a 9.14-m (30-ft) Parshall flume and a ramp flume. The Parshall flume was estimated to cost \$100,000, and the ramp flume was estimated to cost between \$46,000 to \$60,000. The 9.14-m (30-ft) Parshall flume had to be used rather than a 6.10-m (20-ft) flume because of head loss problems. In this case the costs are not as small as cited in [1] (one-tenth to one-third) for small ramp flumes. However, expected savings would diminish with increase in size because flume foundation requirements become more similar, but cost savings are still substantial for large ramp flumes. Thus, a large ramp flume should be built in the field. The flume could be either permanent or temporary and studied during the early stages when the project is operating below design capacity so that more freeboard versatility is available for checking possible scale effect on submergence depth limit.

BIBLIOGRAPHY

[1] Clemmens, A. J., and John A. Replogle. "New Flume Breakthrough for Ditch Irrigation." *Irrigation Age*. April 1978.

[2] ______ . "Constructing Simple Measuring Flumes for Irrigation Canals." *Farmers Bulletin No. 2268*. Water Conservation Laboratory, Agricultural Research Service, Phoenix, Arizona, March 1980.

[3] Replogle, John A., "Compensating for Construction Errors in Critical-Flow Flumes and Broadcrested Weirs." *National Bureau of Standards Special Publication 484*, Symposium on Flow in Open Channels, Gaithersburg, Maryland, February 23-25, 1977.

[4] ______ and A. J. Clemmens, "Modified Broad-Crested Weirs for Lined Canals," *Proceedings of Specialty Conference of the Irrigation and Drainage Division*, Today's Challenges in Irrigation and Drainage, American Society of Civil Engineers, Boise, Idaho, July 1980.

[5] Replogle, John A., and M. G. Bos, "Advances in Irrigation, Flow Measurement —Applications to Irrigation Water Management," ch. In: *Advances in Irrigation*, vol. 1, Daniel I. Hillel, Ed., Academic Press, July 1982.

[6] Replogle, John A., "Critical-Flow Flumes with Complex Cross Section," In: *Proceedings of Specialty Conference of the Irrigation and Drainage Division*, Competition for Resources, American Society of Civil Engineers, Logan, Utah, August 1975.

[7] Bos, M. G., Ed., Discharge Measurement Structures, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 1976.

OTHER REFERENCES

Replogle, John A., "Tailoring Critical-Depth Measuring Flumes," Flow, Its Measurement and Control in Science and Industry, vol. 1, pt. 1, Rodger B. Dowdell, Ed., Instrument Society of America.

______ , "Critical-Depth Flumes for Determining Flow in Canals and Natural Channels," *Transactions of American Society of Agricultural Engineers*, vol. 14, No. 3, March 1971.

______ , "Selecting and Rating Meters for Open-Channel Flows," In: *Proceedings of Specialty Conference of the Irrigation and Drainage Division*, Water Management for Irrigation and Drainage, American Society of Civil Engineers, Reno, Nevada, July 1977.

______ . "Flumes and Broadcrested Weirs Mathematical Modeling and Laboratory Ratings," USDA, Sci. & Educ. Adm., Phoenix, Arizona, Flow Measurement of Fluids, Proceedings of Conference on Flow Measurement 1978, International Measurement Confederation Tech. Comm. on Flow Measurement Conference, Groninsen, Netherlands, September 11-15, 1978, published by North-Holland Publishing Company, Amsterdam, The Netherlands, and New York, New York, pp. 321-332, 1978.

Table 1. — *Percent difference of discharge using head from a location other than the measuring station*

Piezometer location distance upstream from ramp toe		Discharge m³/s (ft³/s)				
ft	m	1.41 (50)	1.13 (40)	0.85 (30)	0.57 (20)	0.28 (10)
			Percent			
0	0	-3	-3	-0.7	-2.5	-5.0
0.5	0.15	-2	+1.25	-0.7	-0.5	-5.0
1.0*	0.30*	--	--	--	--	--
1.5	0.46	0	+0.5	-0.4	-0.5	-2.0
2.0	0.60	0	0	0	0	0
2.5	0.76	0	0.5	0.7	0.4	0
3.0	0.91	0	0.5	0.7	0.5	-2.0

* Measuring station.

Table 2. — *Coefficients and exponents for equation* and percent comparison between the* least squares fit *and the* measured discharge *for four different length crests of about 0.3-m (1-ft) height*

Crest length		*Coefficient A		*Exponent *n*	Percent comparison
ft	m	in-lb system	SI system		
1.5	0.46	19.41	4.857	1.834	±3.0
3.0	0.91	18.63	4.362	1.778	±3.5
3.53	1.08	18.83	4.472	1.790	±4.0
5.25	1.60	18.54	4.367	1.783	±2.5

* For discharge $Q = Ah_1^n$, m³/s (ft³/s). h_1 = measuring head, m (ft).

Table 3. — *Accuracy estimates determined from calibration curves*

1 Crest length ft	m	2 Percent deviation of model discharge from computer discharge at 0.27-m (0.9 ft) measuring head	3 Percent deviation of model discharge from computer discharge at max discharge (head = ½ crest length)	4 Percent maximum deviation of model discharge from model curve fit	5 Maximum discharge[2] ft³/s	m³/s	6 Maximum measuring head[2] ft	m
1.5	0.46	[1]	--	--	11	0.31	0.75	0.229
3.0	0.91	+2	+2½	±1½	38	1.08	1.50	0.457
3.53	1.08	+3	+4	±1	54	1.53	1.75	0.533
5.25	1.60	+3½	+3	±1½	[3]		2.63	0.802

[1] Head violates design criteria equation (5)
[2] Based on design criteria equation (5)
[3] Not enough model depth to determine

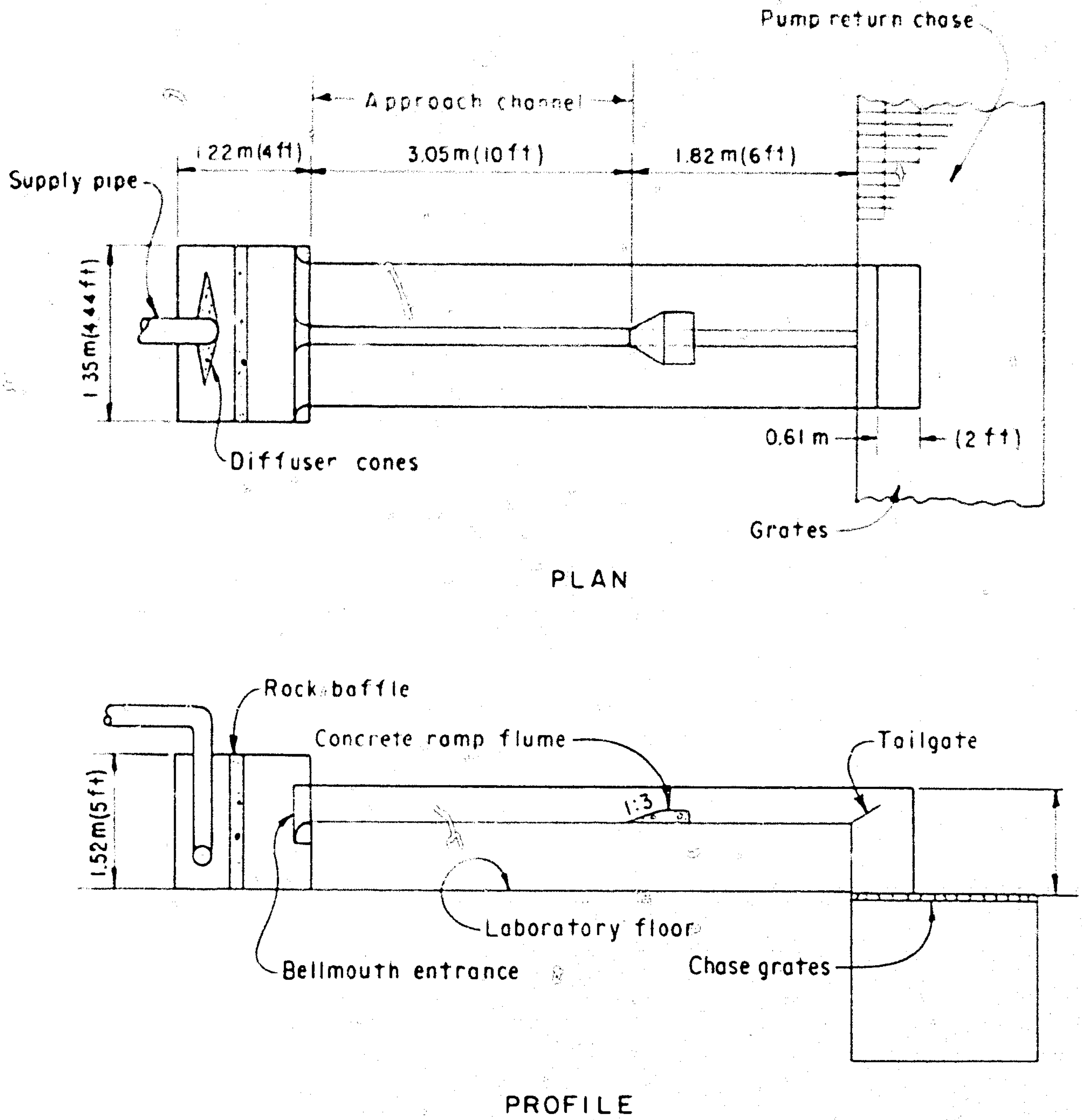


Figure 1. — Laboratory ramp flume — model test arrangement

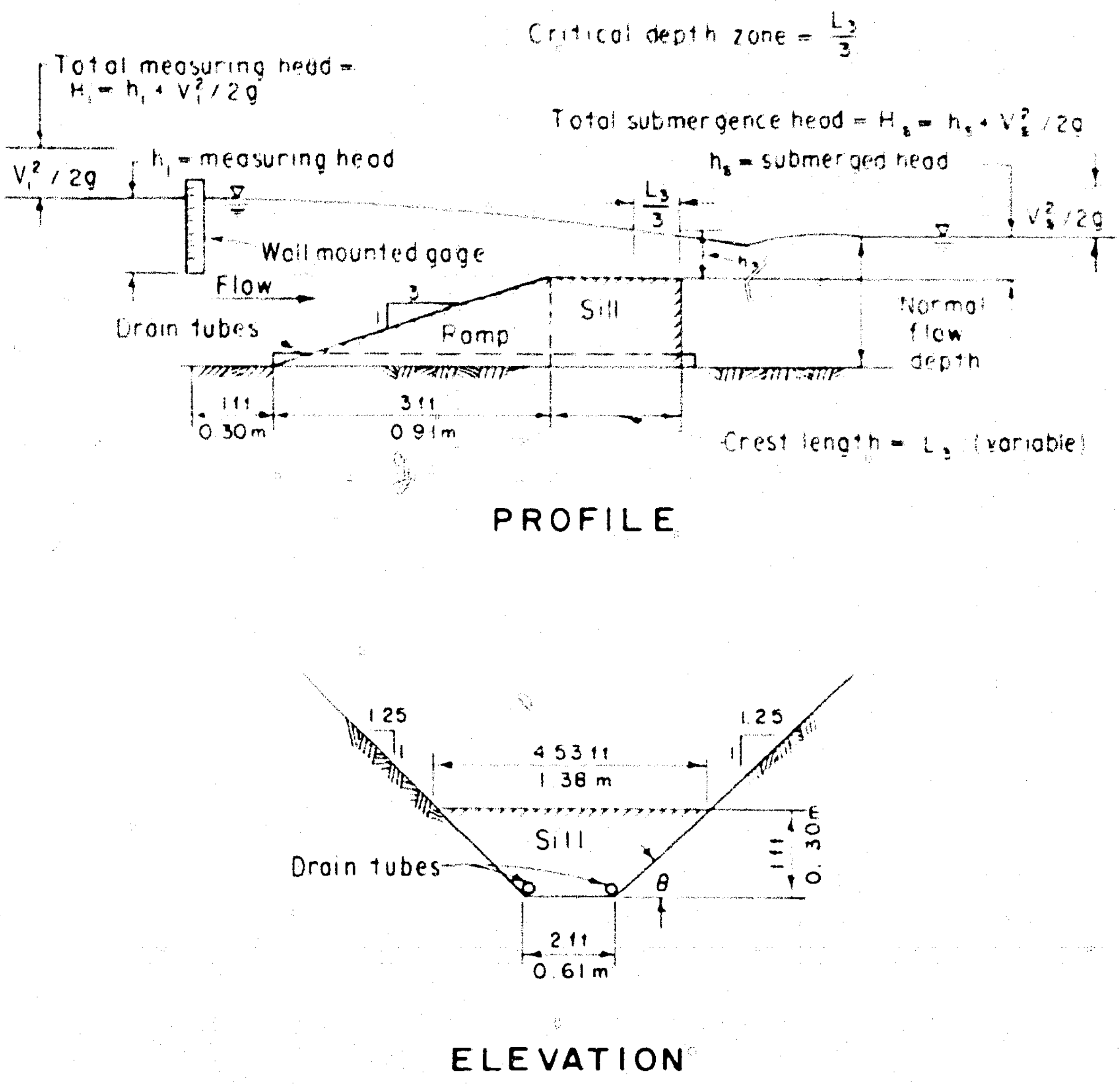


Figure 2. — Details of concrete ramp flume tested

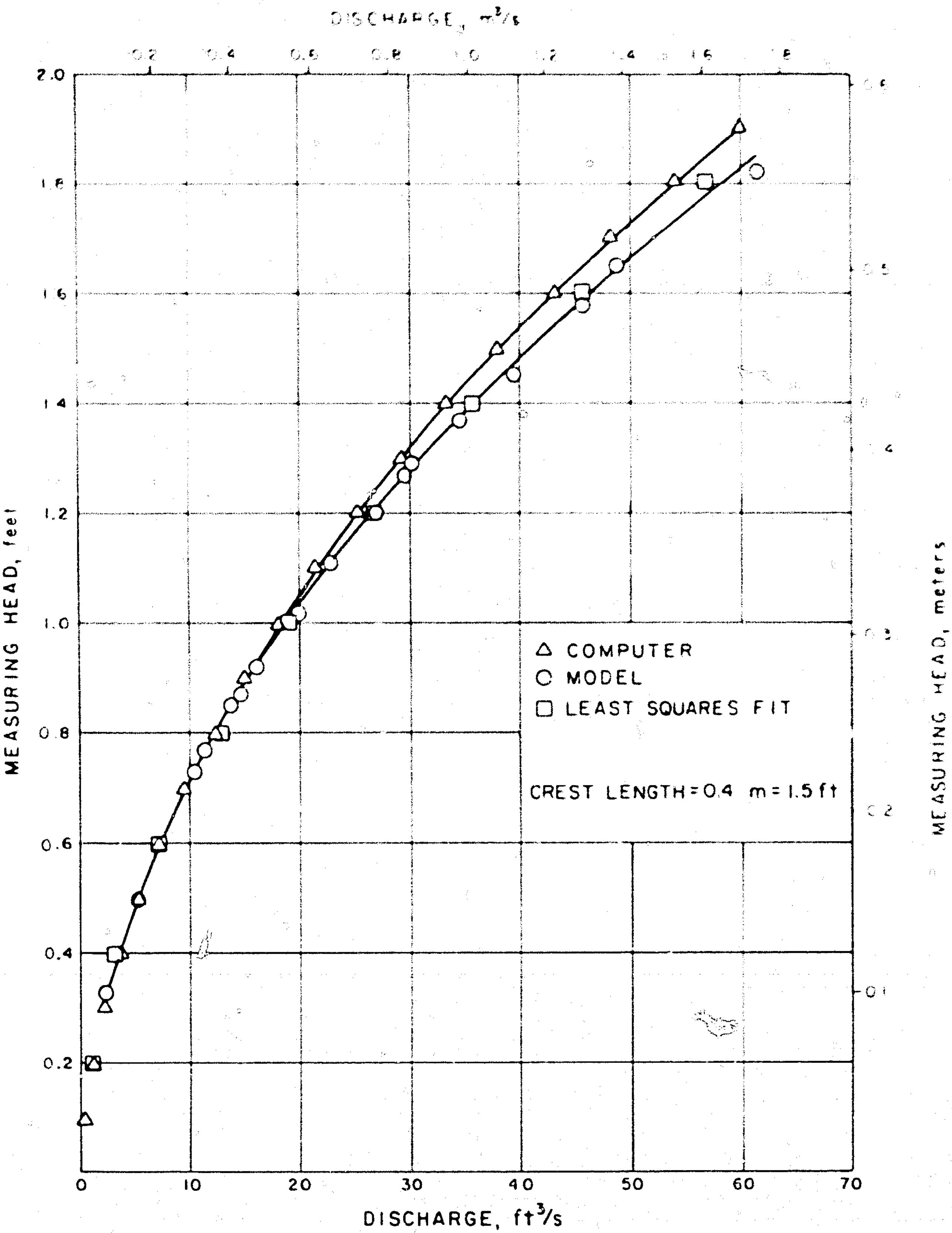


Figure 3. — Ramp flume calibration curve for 0.3-m high crest by 0.46-m crest length (1- by 1.5-ft)

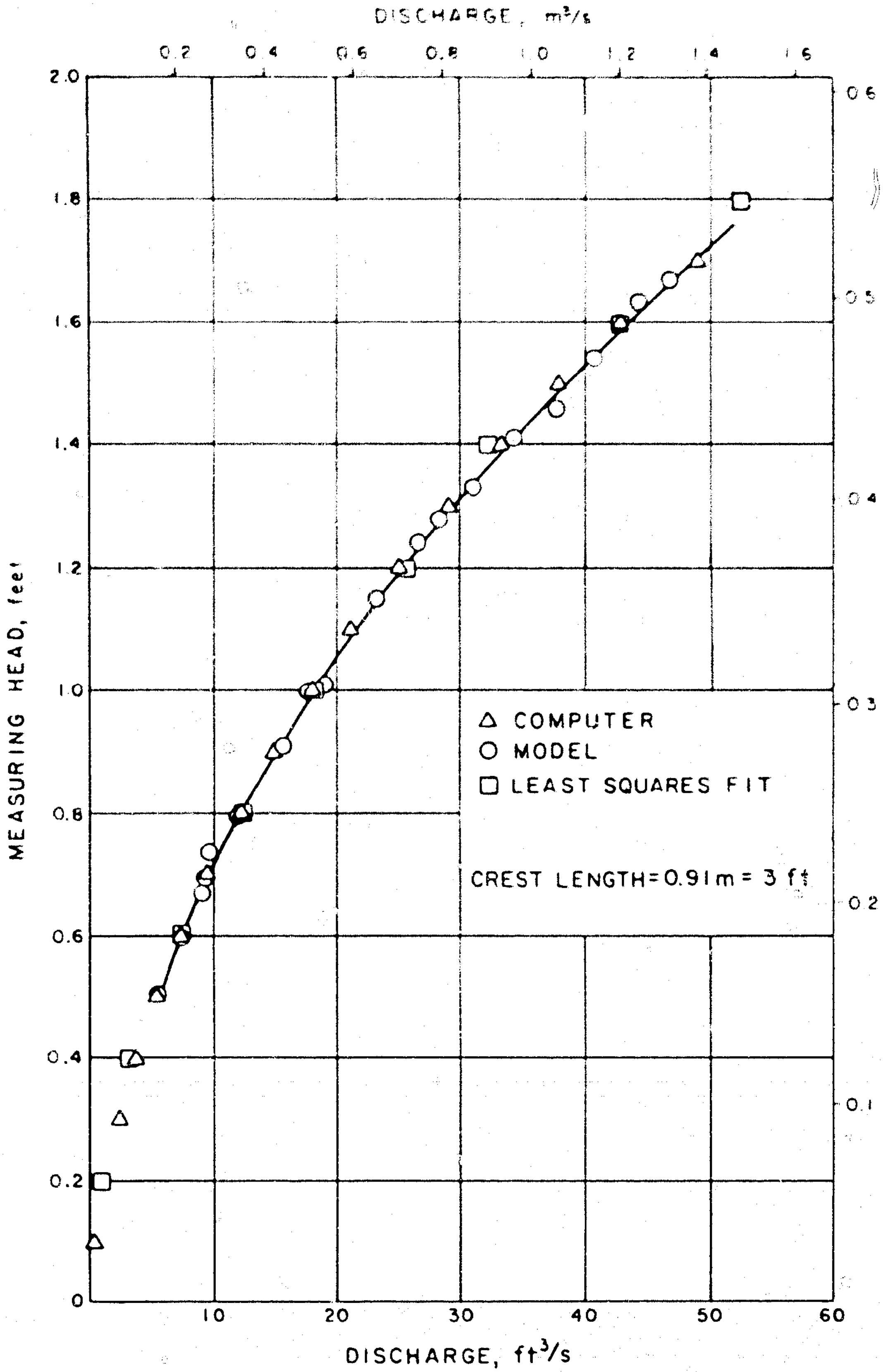


Figure 4. — Ramp flume calibration curve for 0.3-m high crest by 0.91-m crest length (1- by 3.0-ft)

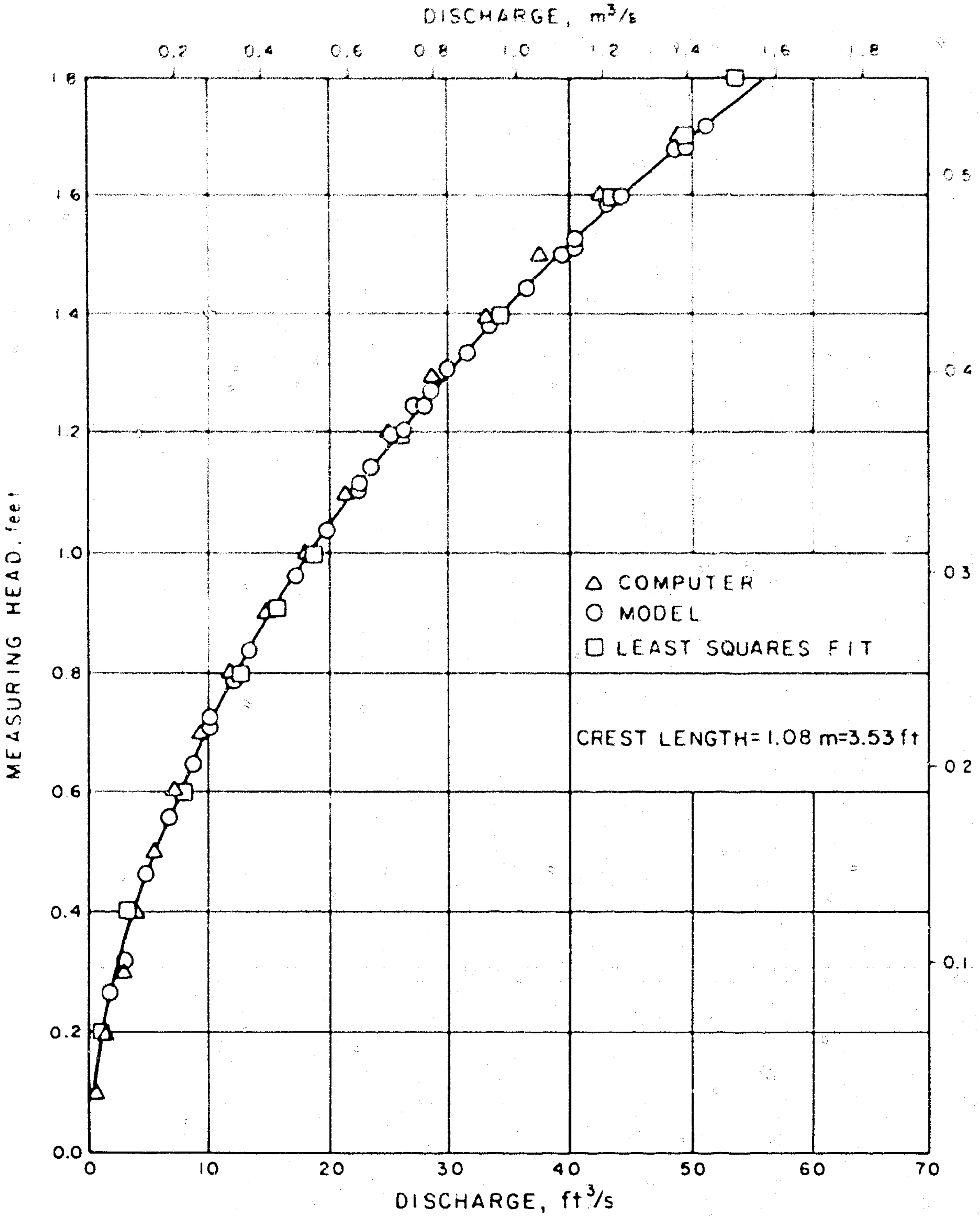


Figure 5. — Ramp flume calibration curve for 0.3-m high crest by 1.08-m crest length (1- by 3.53-ft)

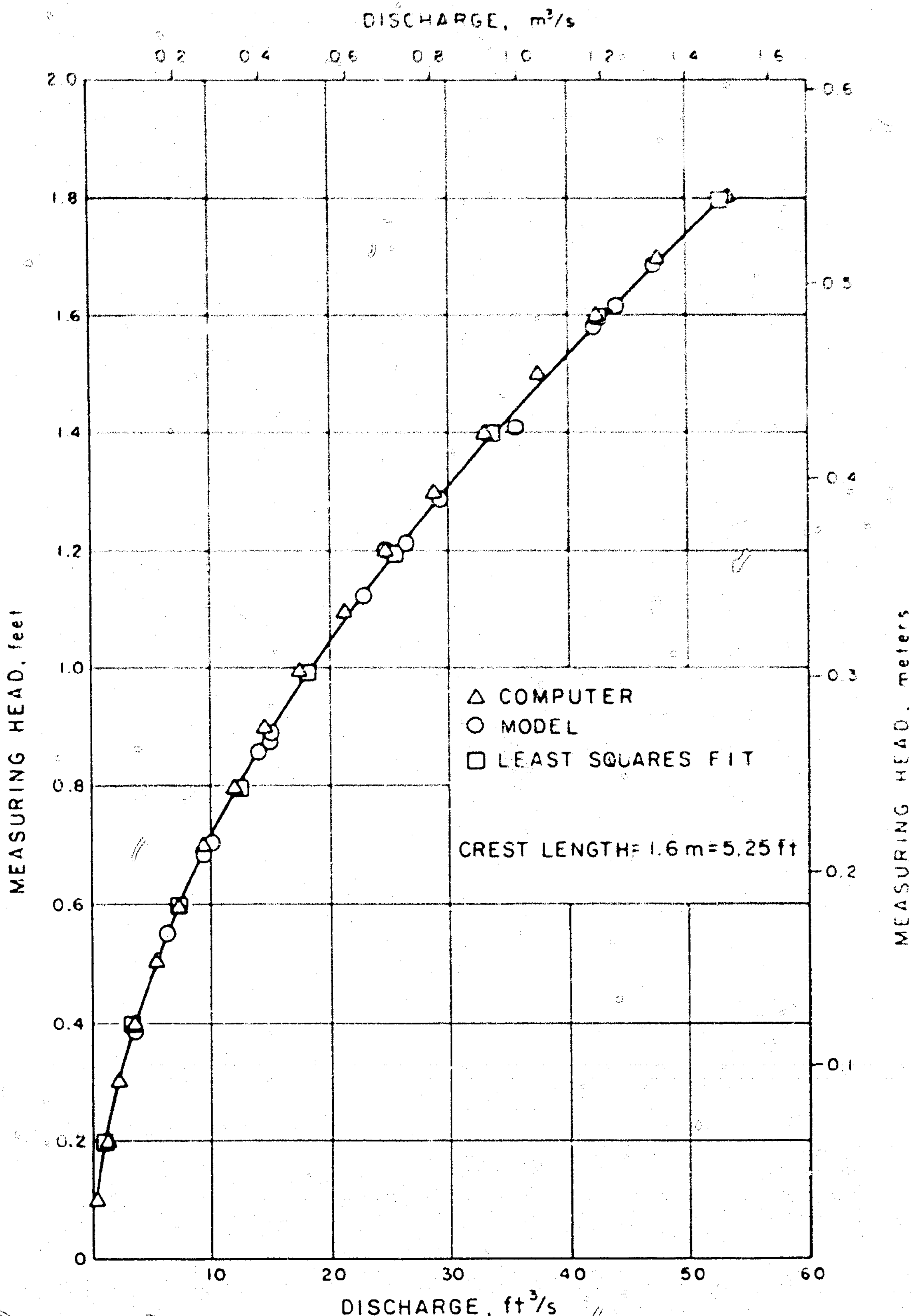


Figure 6. — Ramp flume calibration curve for 0.3-m high crest by 1.6-m crest length (1- by 5.25-ft)

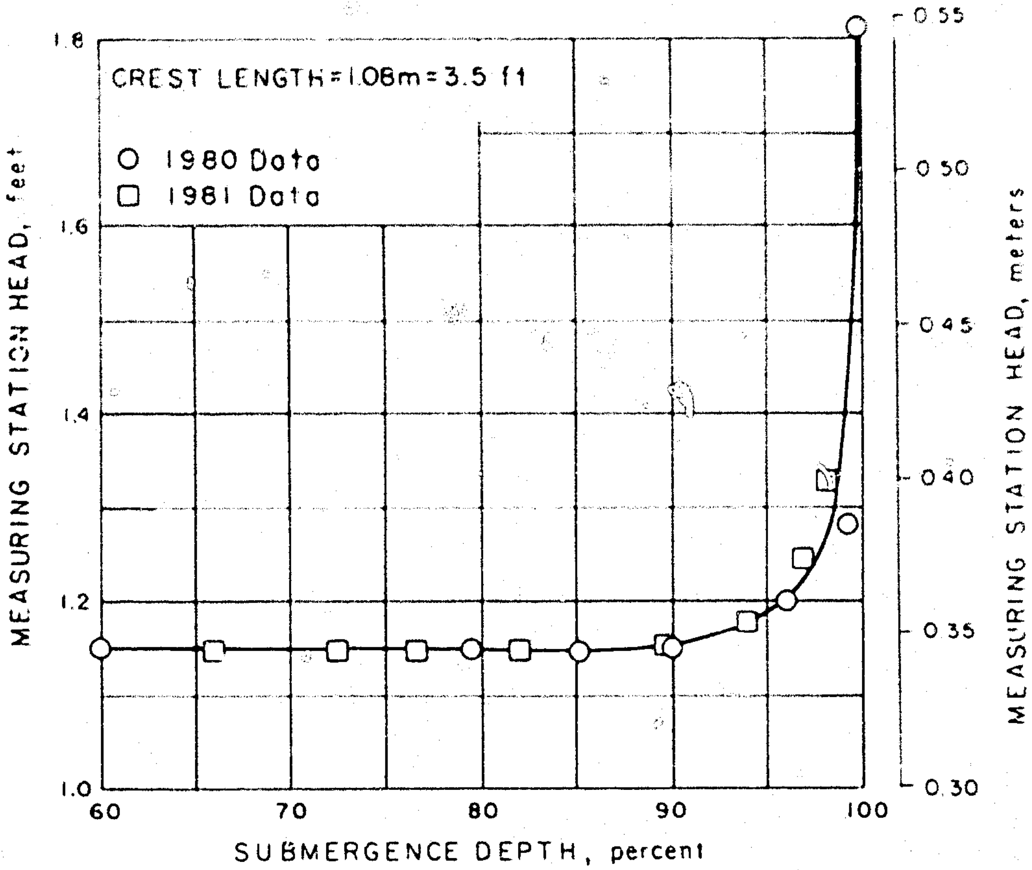
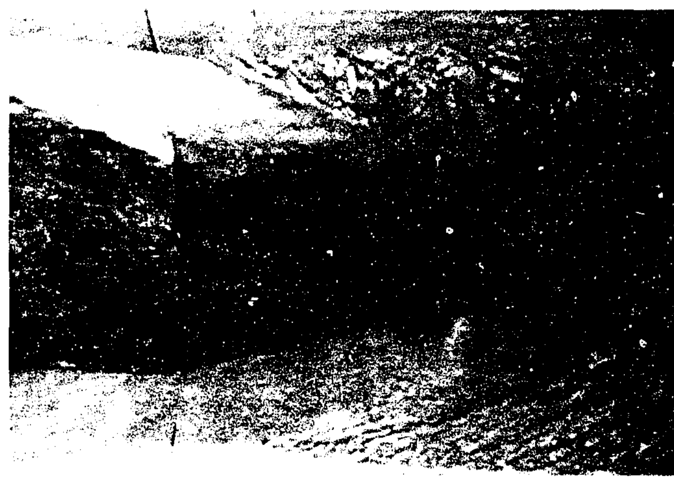
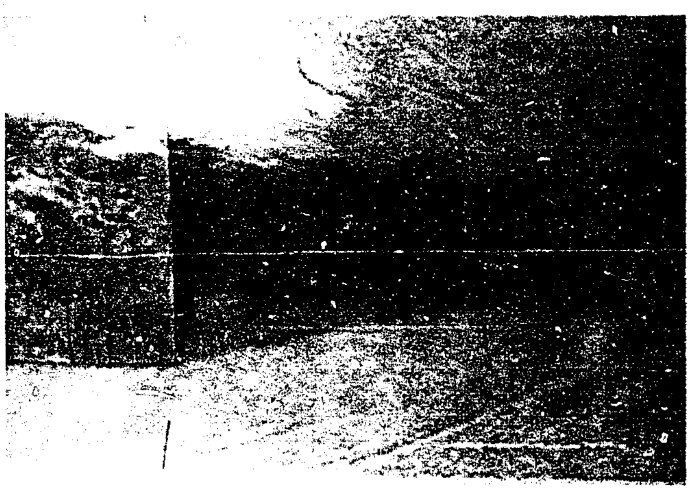


Figure 7. — Ramp flume submergence characteristics for discharge of 0.67 m^3/s (23.6 ft^3/s)

a. Submergence less than 85 percent. Photo P801-D-80115

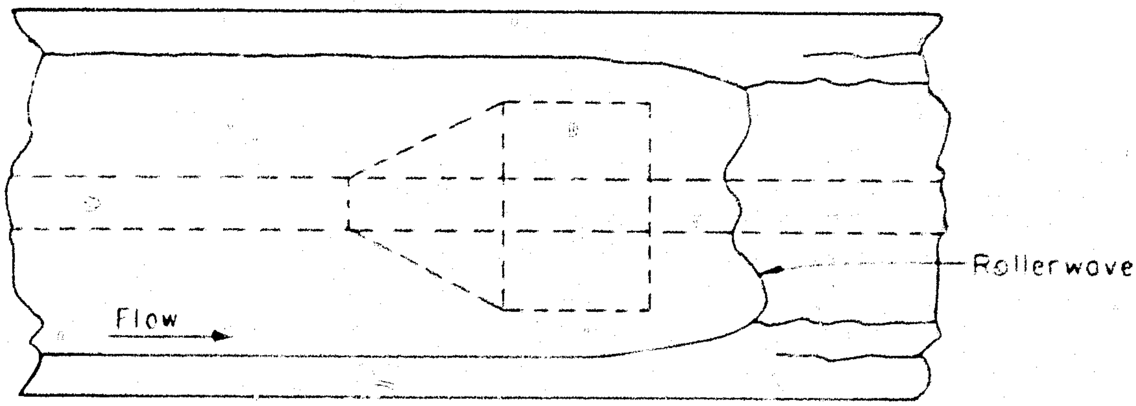
b. Submergence limit 85 percent. P801-D-80116



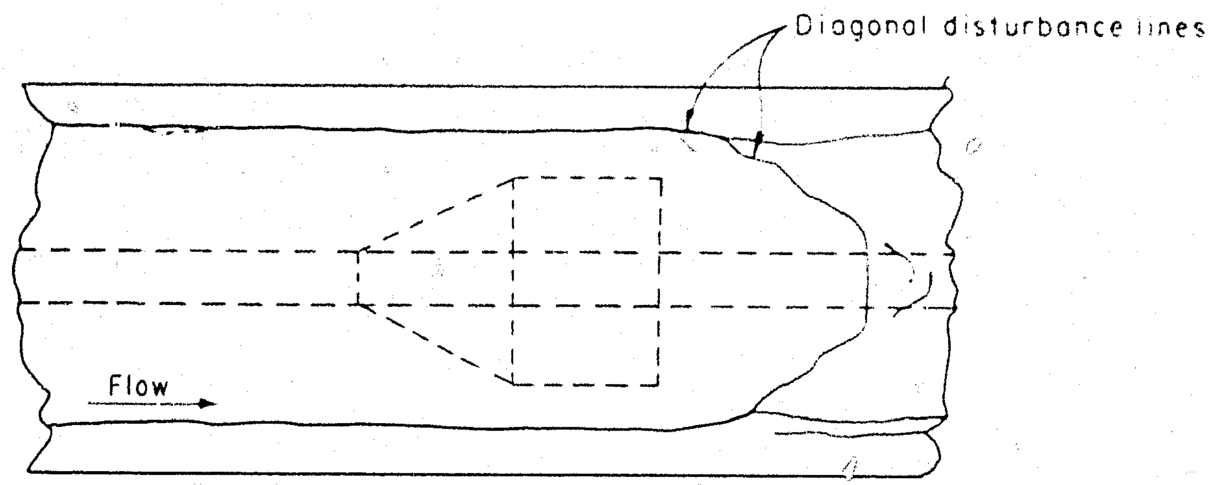


c. Submergence greater than 85 percent. P801-D-80117

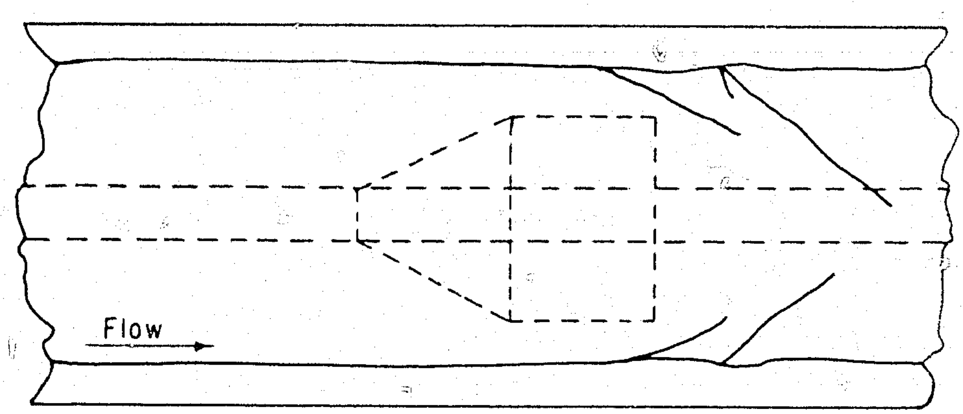
Figure 8. – Waveforms downstream of ramp flume having a 1.08-m crest length (3.53-ft) —flow left to right



(a) Submergence less than 85 percent



(b) Submergence limit 85 percent



(c) Submergence greater than 85 percent

Figure 9. — Waveform sketches downstream of ramp flume

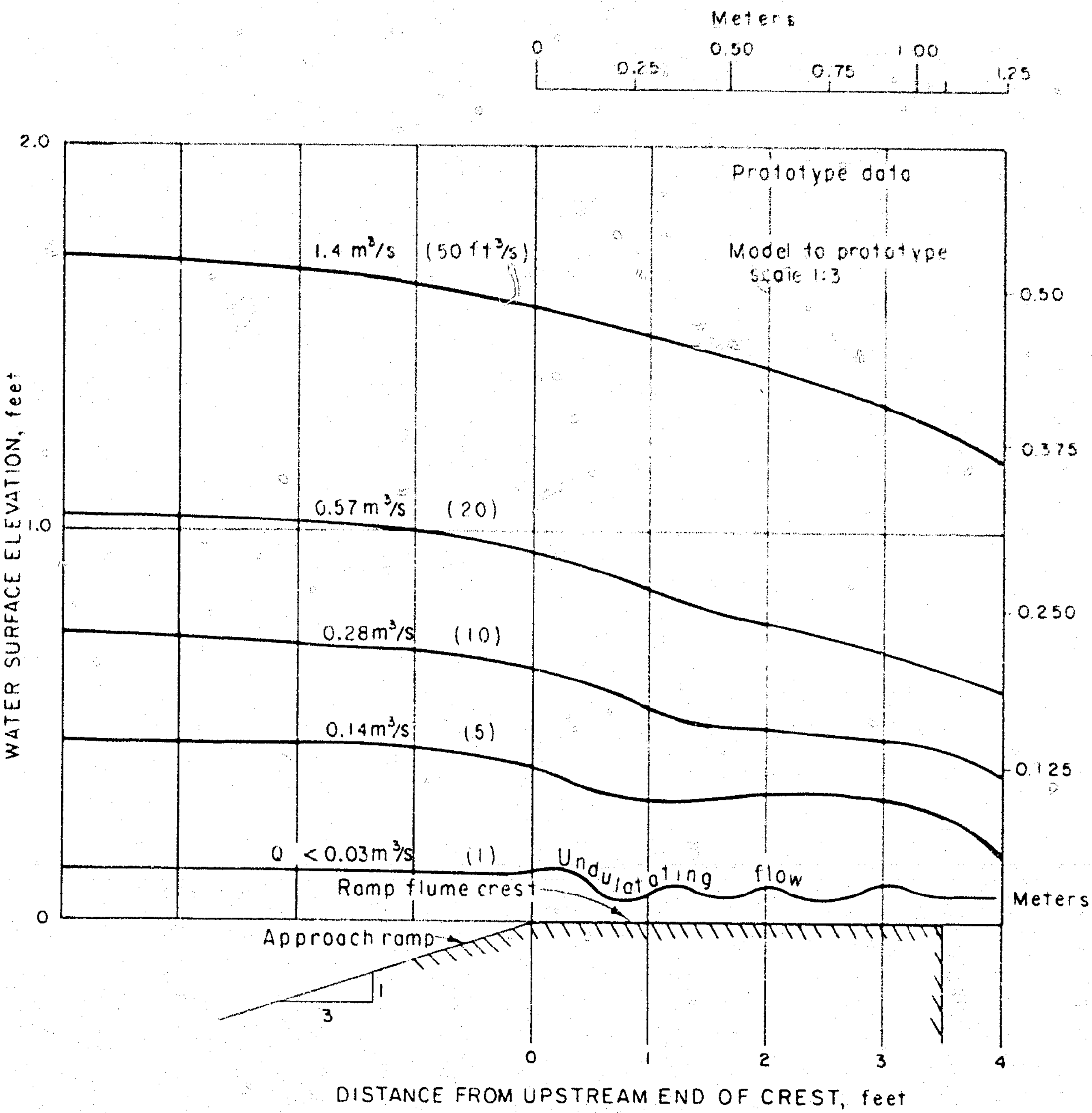


Figure 10. — Water surface profiles for various discharges — crest length 1.08 m (3.53 ft)

GPO 839-593

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-922, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.