PAP-438

PROGRESS SUMMARY

RAMP FLUME MODEL STUDY

BY

RUSSELL A. DODGE

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ABSTRACT

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

The flumes can be computer calibrated using after-construction dimension measurements. With a vertical drop at the end of the crest, the measuring device can tolerate a submergence of 85 percent. With a 6:1 ramp diverging from the end of the crest to the bottom of the canal, the measuring device can tolerate 93 percent submergence. The results of laboratory testing indicate that these water measuring devices have a strong potential for measuring flow in canal systems.

CONTENTS

TABLES

FIGURES

CONTENTS - Continued

FIGURES

ACKNOWLEDGMENTS

This study was conducted in the Hydraulic Research Section, Hydraulics Branch, Division of Research, and supported by the 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 select dimensions for a possible ramp flume for the Charles Hansen feeder canal and did some computer studies on the effects of variables changes. John Replogle provided E. J. Carlson, who supervised these studies, two programs for making computer calibrations. Jerry Martin modified one of these programs to output appropriate warnings when certain design criteria are violated.

PURPOSE

The progress covered in this report 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.

INTRODUCTION

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

Various articles by Replogle and Clemmens (see bibliography) indicate that the ramp flumes are easy to install in existing canals to meet after-the-fact water-measuring requirements for operation and conservation needs. Small or farm ditch size ramp flumes are reported to cost one-tenth to one-third of Parshall flumes [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 [3] have been cited and could approach 95 percent for long throated flumes, with an added 6:1 downstream ramp [7, 8]. Another cited advantage is that they can be computer calibrated using after-construction dimension measurements. Thus, form slipping and construction errors can be accounted for accurately allowing more tolerance during construction.

Ramp flumes are reported to have no more significant problems with sediment [12] 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 flow accelerates, it is expected that most sediment traveling in the approaching canal will go over the ramp [12].

Water Operation and Maintenance Bulletin No. 107 completely reproduced the article by Messrs. Clemmens and Replogle from the April 1978 issue of Irrigation Age, "New Flume Breakthrough for Ditch Irrigation" [1], describing some Arizona Agriculture Research Center experience with ramp flumes.

The Upper Missouri Region is using some ramp flumes as checks and is planning to install more. The Chief, Design Branch, Billings, Montana, contacted the Hydraulics Branch and asked if we had any experience or data verifying the claimed accuracy for using ramp flumes as measuring devices. Our lack of experience was the main reason for this study and investigation.

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* Numbers in brackets indicate references at the end of this report.

Mr. Replogle provided Mr. E. J. Carlson, E&R Center, with two computer programs: One is a BASIC program for calibrating simple trapezoidal flumes and the other is a FORTRAN program capable of calibrating complex trapezoidal flumes with multiple side slopes in the approach and throat section.

CONCLUSIONS

1. Accuracy comparisons of 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 and have a potential accuracy of 2 to 3 percent.

2. The computer programs have been modified to output limit warnings where submergence limit, the Froude number criteria, and crest length criteria have been violated, so inexperienced users will provide sufficient design data.

3. The main construction requirements are that the crest is of proper length and is 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 carefully measured after construction. A calibration is especially sensitive to the crest width dimension. Ramp flumes can be computer calibrated, using the after-construction dimension measurements. Thus, form slipping and construction errors can be accounted for accurately. Computer calibration 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 in order to approach a potential accuracy of 2 to 3 percent.

5. The 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 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 general research program should be started using our laser-Doppler anemometer to determine velocity distribution coefficients in terms of Reynolds number and shape to improve mathematical hydraulic modeling.

8. Submergence data obtained from the model with the vertical drop determined a submergence limit of about 85 percent, agreeing with the claimed submergence limit for small ramp flumes at which the discharge deviates 1 percent from the free flow head-discharge relationship. Therefore, the

minimum required head loss was 15 percent. For the model ramp flume with 6:1 downstream diverging ramp, the submergence limit was about 93 percent.

9. Pressure measurements indicated that the ramp flumes are relatively insensitive to measuring station location. A measuring station location 0.30 m (1 ft) upstream of 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 about 45 to 60 percent of that for a Parshall flume in a retrofit situation. Replogle cited costs of one-tenth to one-third of equivalent Parshall flumes for small ramp flumes. This cost scale effect was probably due to more common foundation requirements for both Parshall and ramp flumes of large sizes.

11. Because of 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 the field calibration, the submergence limit should be determined to see if there is a scale effect, similar to Parshall flumes, causing increased tolerance of larger ramp flumes to submergence.

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.

BASIC PRINCIPLES

Weir Regimes and Crest Length Criteria

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

When $(H_1/L_3) < 0.08$, friction of the crest controls and undulations can occur on the crest. (1)

When $0.08 \leqq (H_1/L_3) \leqq 0.33$, 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 is operating between these limits, is it operating in a true broad-crested manner. (2)

When $0.33 < (H_1/L_3) <$ from about 1.5 to 1.8, 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. (3)

When $(H_1/L_3) >$ about 1.5, 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. (4)

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

$$0.05 \leqq (H_1/L_3) \leqq 0.50 \tag{5}$$

To prevent wave interference, Replogle further specifies an upper limiting Froude number $V/\sqrt{gD_1}$ of 0.5 for the approach flow.

where: g = acceleration of gravity

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

The ramp flume is basically a critical-depth measuring device. In his computer programs, Replogle uses the relationship for discharge (Q) at critical depth for any shape channel expressed as

$$Q = (gA_3^3/\alpha_3\ T_3)^{1/2} \tag{6}$$

where symbols not previously defined are:

Q = discharge

A_3 = area at the critical depth or control location which varies with discharge somewhere in the downstream one-fourth to one-third of the crest length

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

T_3 = top width at the control section

V_3 = velocity at the control section

He used the energy relationship for the reach between the measuring station and critical depth location with friction loss H_f included and expressed as

$$h_3 = h_1 + \alpha_1\ (Q^2/2gA_1^2) - A_3/2T_3 - H_f \tag{7}$$

where h_1 = measuring station head relative to crest
h_3 = control station head relative to crest

Mr. Replogle has developed computer routines to determine the velocity distribution coefficient α_3 for wide flow and friction loss during boundary layer development. The computer program assumes that α_1 is 1.04 and that design criteria relationship (5) makes flow sufficiently parallel so that curvature effect is insignificant.

THE MODEL

Laboratory Flume and Measuring Techniques

The Upper Missouri Region personnel were using ramp flumes for checking flows up to 1.42 m^3/s (50 ft^3/s). Since the Hydraulic Laboratory cannot supply this much flow, 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 1:1-1/4 side slope and was about 4.88 m (16 ft) long with a top width of 1.04 m (3.4 ft) and a depth of about 0.34 m (1.11 ft). A headbox with a rock stilling and distribution baffle and a bellmouth entrance to the canal section was provided to smooth the approach flow. A downstream flap gate was installed to vary submergence. The ramp and crest were poured in concrete formed as shown in figure 2.

Flow through the ramp flume was measured by means of volumetrically calibrated venturi meters. The venturi meters are an integral part of the permanent Hydraulic Laboratory facility and can easily measure discharge to within plus or minus 1 percent and have a potential accuracy of plus or minus one-half of 1 percent.

Measuring and submergence heads were transmitted to hook gage wells by plastic tubing for more accurate measuring. Repeatability of reading the water surface elevation with hook gages in the wells was 0.3 mm ($\pm$0.001 ft). The measuring head was measured 0.30 m (1 ft) 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 0.405 m (1.33 ft) from the flap gate. This location was considered too close to the downstream control flap gate to study submergences with a 6:1 downstream diverging ramp 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 zeroed with respect to the ramp flume crest. Pressures were transmitted to a pressure cell with a digital voltage display scaled to read pitot differential directly in feet of water.

RESULTS

Test of Location for Measuring Station

The 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. Some devices deliberately place the measuring station in the accelerating part, making installation of pressure taps or staff gages a critical construction measurement in terms of accuracy. One presumed advantage of doing this is that the measuring station is located within the device itself, providing better control for prefrabricated 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 with the measuring station values. Error of discharge due to water surface curvature or to using another location than the calibration measuring station was determined. Discharge error for the tap at the ramp toe ranged from -1-3/4 to -5 and averaged about -3 percent. At 0.15 m (0.5 foot) from the toe, the discharge error ranged from +1-1/4 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 plus or minus 0.7 percent. For some unknown reason, the error at 0.28 m^3/s (10 ft^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 head other than measuring station head 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 measuring station distance plus the ramp length is greater than five measuring heads should be minimized. Doing this maximizes the range of flow that matches the computer assumption that contraction and roughness control exclusively. Measurements made in noncompliance with this requirement are not necessarily wrong but should be infrequent.

Model to Computer Calibration Comparison

The laboratory calibrations for 0.45-, 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 in figures 3 through 6, respectively. Curves were fitted by eye through laboratory data. Computer calibrations were made and are triangle symbols on the same plots. Log-log least squares curve fits were also made with the laboratory data of discharge to measuring head. The values of percent difference between least squares fit computed and measured values of discharge were not as small as the writer expected, however. Maximum differences are given in table 2 along with the coefficient A and the exponent n for the equation

$$Q = Ah_1^n \tag{11}$$

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

Table 3 summarizes the comparisons for the model and computer calibrations made from the calibration plots. 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 head equal to one-half the crest length. Column 4 gives the maximum percent deviation of model data about the french curve fit of the model data. Columns 5 and 6 list maximum discharge and measuring head determined on the basis of equation 5. The data in table 3 show that the computer program generally determines calibrations that were always less in discharge for given measuring heads than measured in the model. The data in the table were all within -4 percent of the laboratory calibration which is accurate to plus or minus 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 with 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 vary with shape and hydraulic parameters. With a laser doppler anemometer available in the laboratory, the Bureau should start a general research program to quantify the velocity distribution coefficient α in terms of Reynolds number and shape. Better capability of selecting proper α values would be of considerable help to mathematical modelers in solving hydraulic problems.

<u>Submergence Tests</u>

The submergence depth (fig. 2) limit percentage can be defined as the value of (h_s/h_1)x100 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 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, figure 2, to determine submergence limits (H_s/H_1)x100. Total head submergence limits are generally 1 to 1.5 percent greater than submergence depth limits.

To check 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 of one test for 0.67 m^3/s (23.6 ft^3/s) are plotted in figure 7. This plot and the data for the other two discharges indicate that the submergence depth limit is at about 85 percent and discharge measurement is very sensitive to error just beyond the submergence limit. Visual determination of whether submergence exists is difficult to make near the limit. It requires actual experience of having seen flow near the limit.

Figure 8a shows photographs of 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 is generally 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 in 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 tolerance to submergence. 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 are frequently provided for flow measuring devices, it generally is not considered good practice to use flume-type measuring devices under submerged conditions. Any technique that provides for submergence correction is done with increasing sacrifice of 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 or downstream measuring head station doubles the chances of wrong readings. Submerged discharge ratings are related to small differences of measuring heads. Small imprecisions of water elevation measurement cause large errors. As submergence becomes greater, the measuring head differentials become smaller and approach values that are about the same magnitude as for minor variations of 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. A user can temporarily dam the ditch downstream of the measuring device and then remove the obstruction after the operator has set a flow and gain considerably more than his fair share of water free.

Knowledge of minimum required 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 mainly directed 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 in 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 flows are visibly curved throughout this range of discharge, the assumption of parallel flow for computing measuring heads is apparently close enough to produce computer calibrations that are within -2 to -3 percent. The profile in figure 10 for discharges less than 0.03 m^3/s (1 ft^3/s) is strictly schematic and was drawn to show undulating flow that can occur when friction on the crest controls. The ramp flume would not function as a measuring device in this case.

Velocity Distribution Coefficient

Velocity data were taken on the downstream third point of the crest to calculate velocity distribution coefficient (α) for a discharge of 0.34 m^3/s (12.2 ft^3/s) for 5 vertical profiles; using 5 velocity area zones, α was 1.129; for 11 verticals and 9 zones, α was 1.094; and for 11 verticals and 10 zones, α was 1.065. The computer program computed 1.013 for the same discharge. This does not explain the one-sidedness of the difference between model calibration and computer calibration discussed previously because larger values of computer α_3 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 of three Water Management Workshops. About 80 participants requested copies of any written reports generated by the studies. Denver Office personnel 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. 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. The costs in this case are not as small as cited by Replogle (one-tenth to one-third) for small ramp flumes. However, the writer would expect that savings would diminish with increase in size because foundation requirements become more alike. However, 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 of the project so that freeboard versatility is available to check for possible scale effect on submergence characteristics.

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

Piezometer location distance upstream from ramp toe		Discharge m^3/s (ft^3/s)				
ft	m	1.41 (50)	1.13 (40)	0.85 (30)	0.57 (20)	0.28 (10)
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 English unit equations* and percent agreement for four different length crests of about 0.3-m (1-ft) height

Crest length ft	m	Coefficient* A	Exponent* n	Percent comparison
1.5	0.48	19.41	1.834	±3.0
3.0	0.91	18.63	1.778	±3.5
3.53	1.08	18.83	1.790	±4.0
5.25	1.6	18.54	1.783	±2.5

* For equation $Q = Ah_1^n$

Where Q is discharge ft^3/s.
h_1 is measuring head ft.

Table 3. - Accuracy estimates determined from calibration curves

1 Crest length ft*	2 Percent deviation of model from computer discharges at 0.9-ft measuring head	3 Percent deviation of model discharge from computer discharge at max. discharge	4 Percent max. deviation of model discharge from model calibration	5 Maximum discharge*** ft^3/s	6 Maximum measuring head*** ft
1.5	**	-	-	11	0.75
3.0	+2	+2-1/2	±1-1/2	38	1.50
3.5	+3	+4	±1	54	1.75
5.25	+3-1/2	+3	±1-1/2	****	2.63

* 1 ft = 0.3048 m.
** Head violates design criteria equation (5), page 4.
*** Based on design criteria (5), page 4, 1 ft^3/s = 0.02832 m^3/s.
**** Not enough model depth to determine.

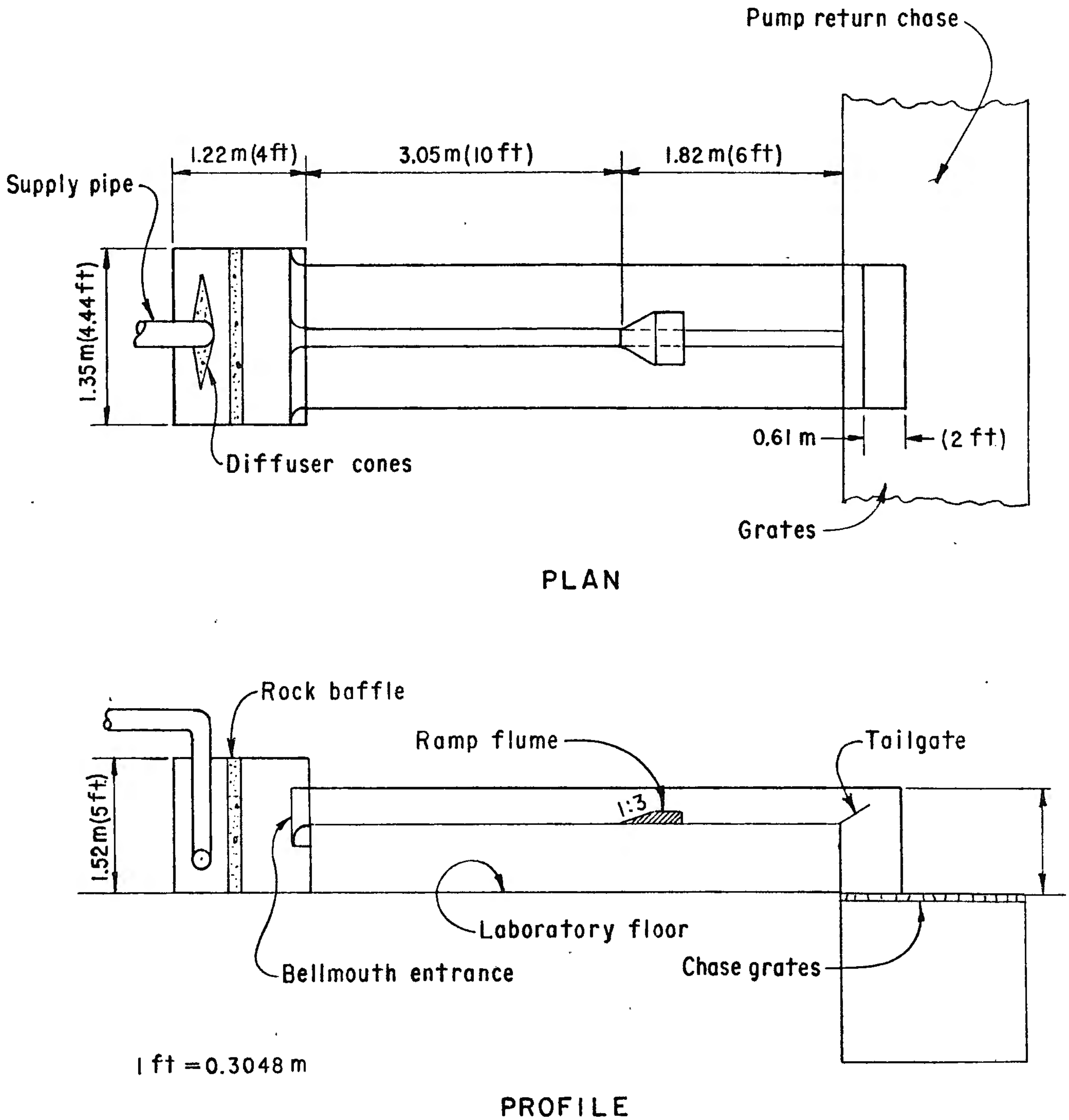
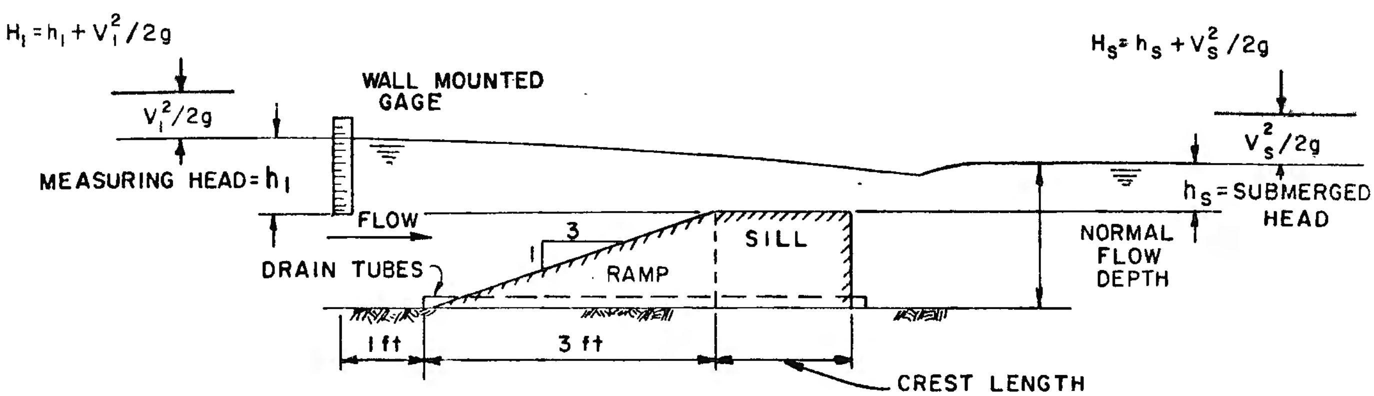
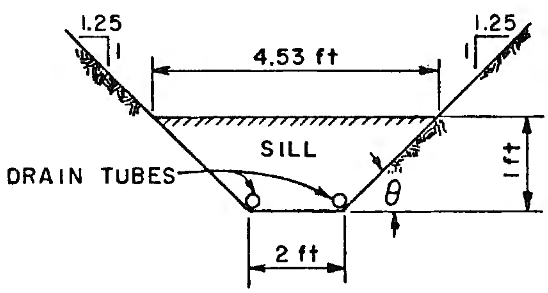


Figure 1. - Laboratory test arrangement.





1 ft = 0.3048 m

Figure 2. - Concrete ramp flume.

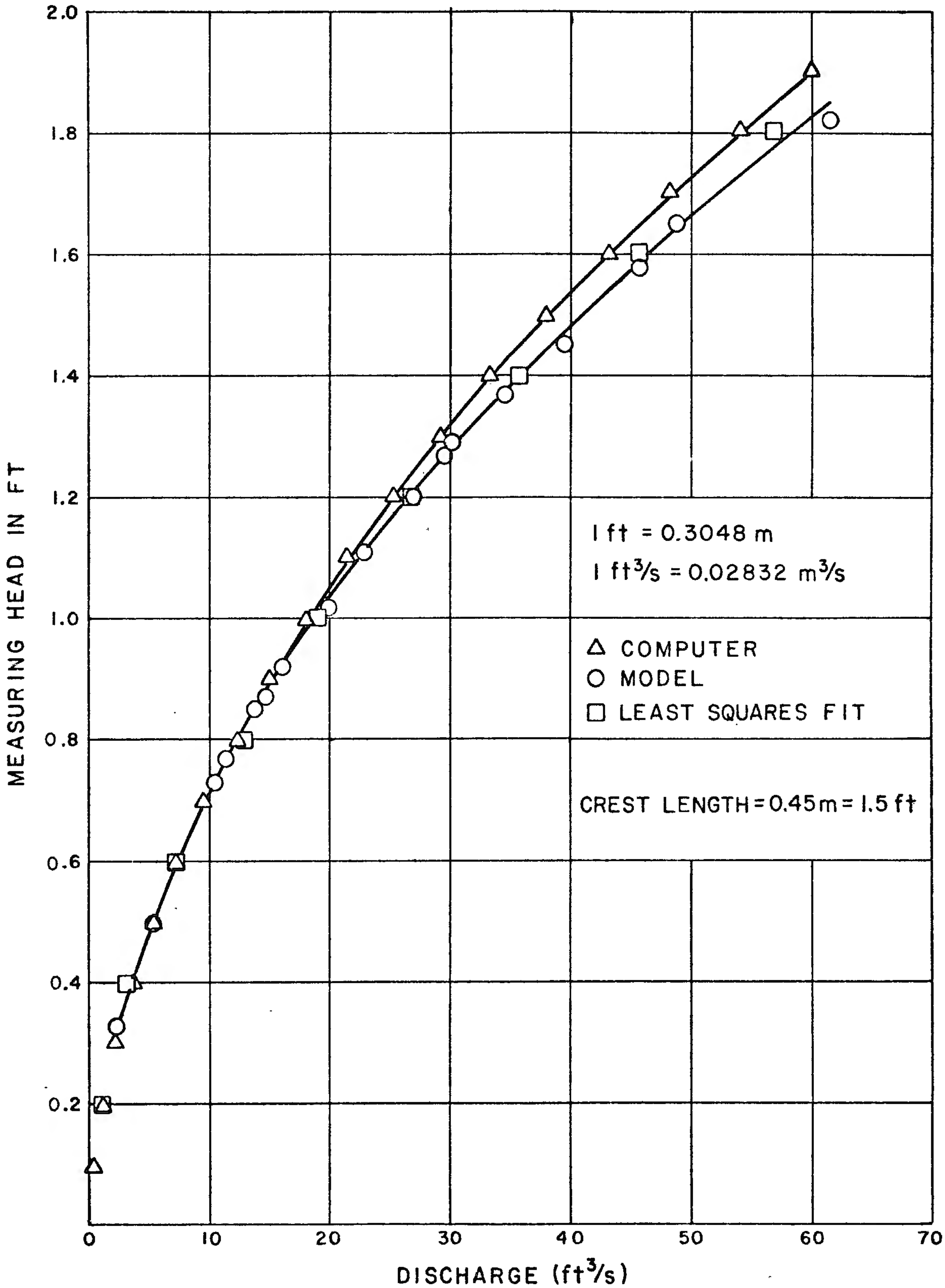


Figure 3. - Calibration curve for 0.3-m (1-ft) high crest and 0.45-m (1.5-ft) crest length.

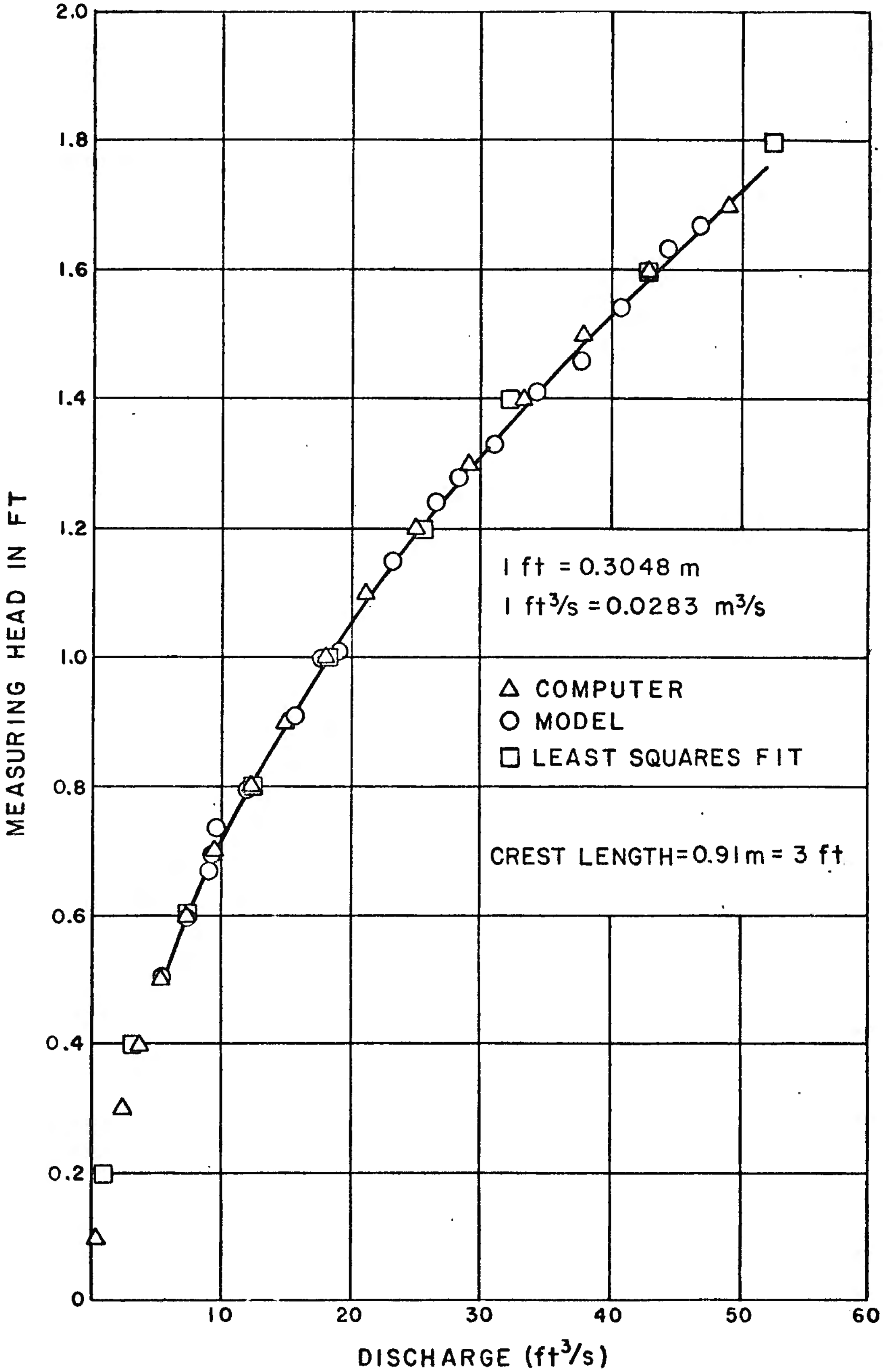


Figure 4. - Calibration curve for 0.3-m (1-ft) high crest and 0.91-m (3.0-ft) crest length.

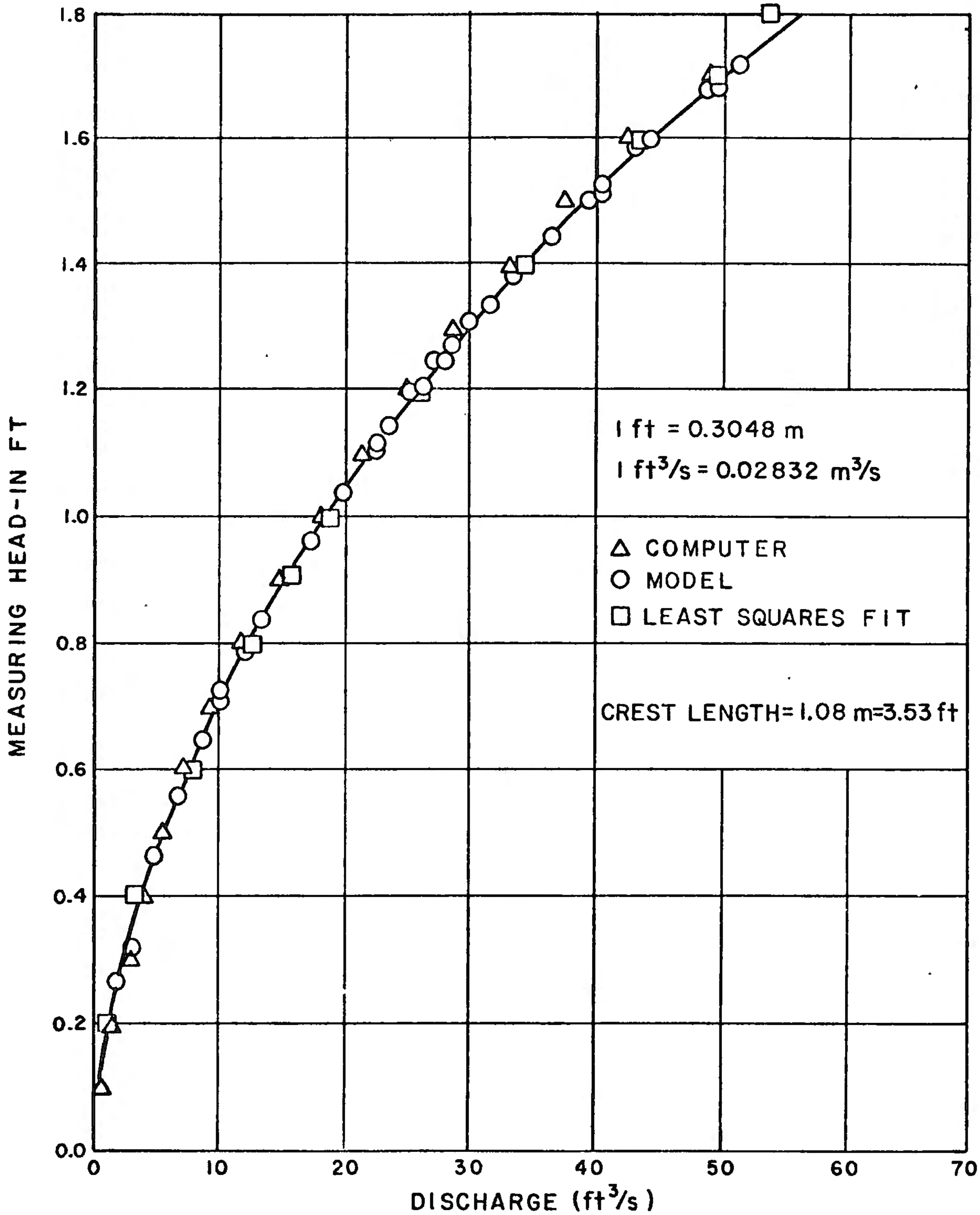


Figure 5. - Calibration curve for 0.3-m (1-ft) high crest and 1.08-m (3.53-ft) crest length.

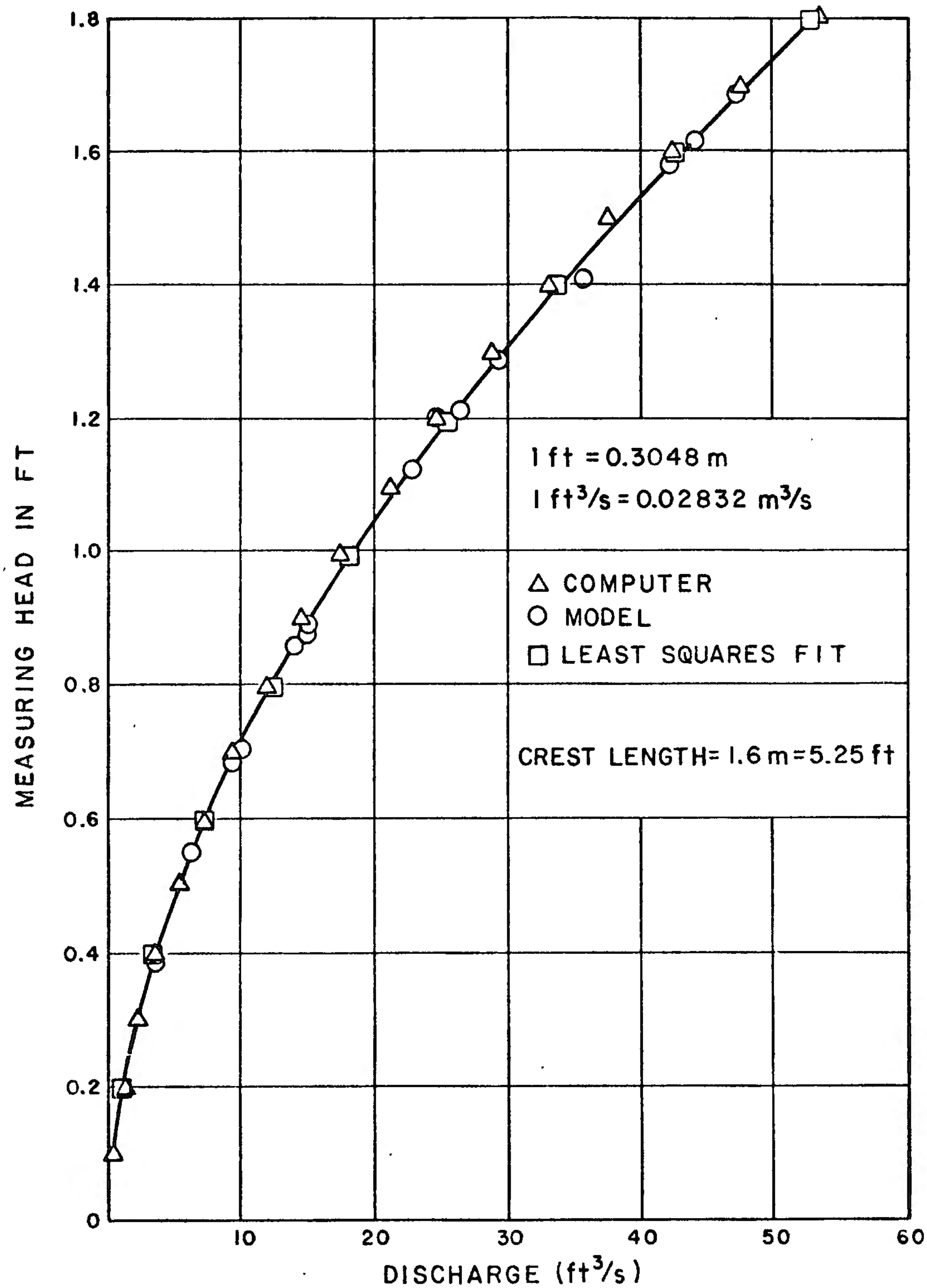


Figure 6. - Calibration curve for 0.3-m (1-ft) high crest and 1.6-m (5.25-ft) crest length.

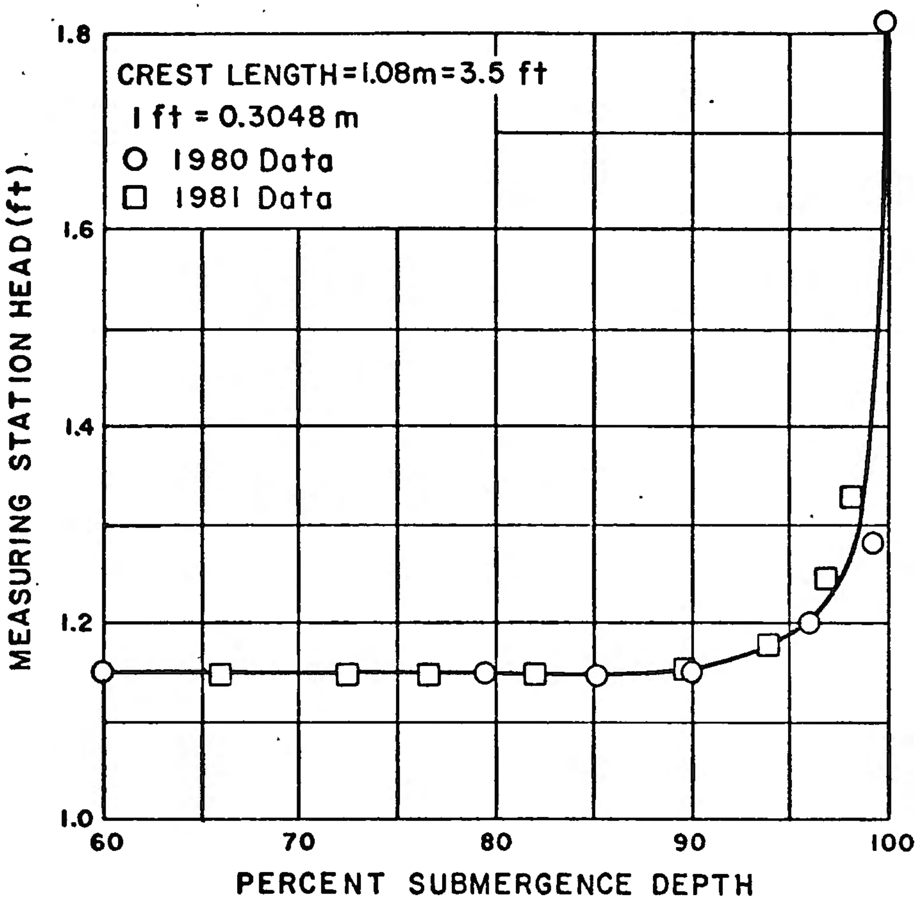
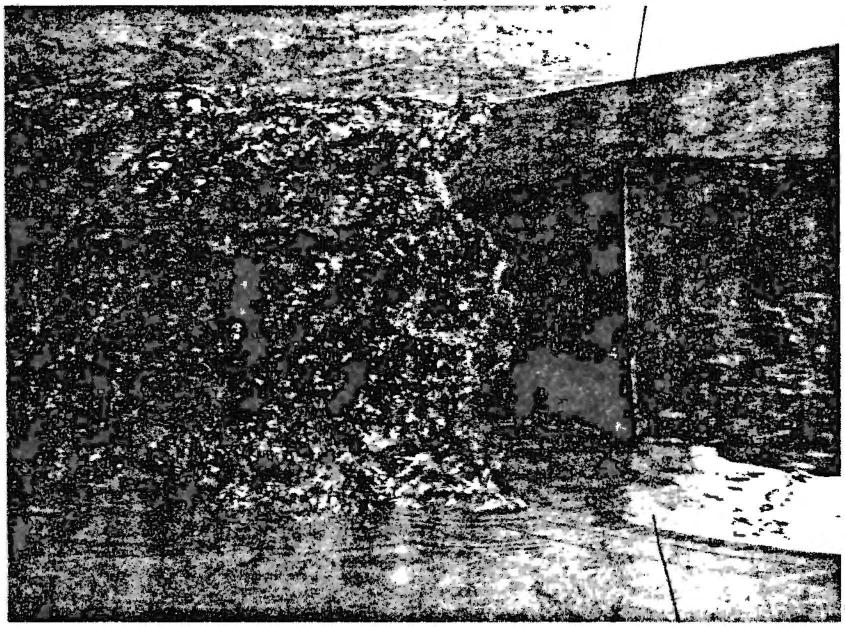
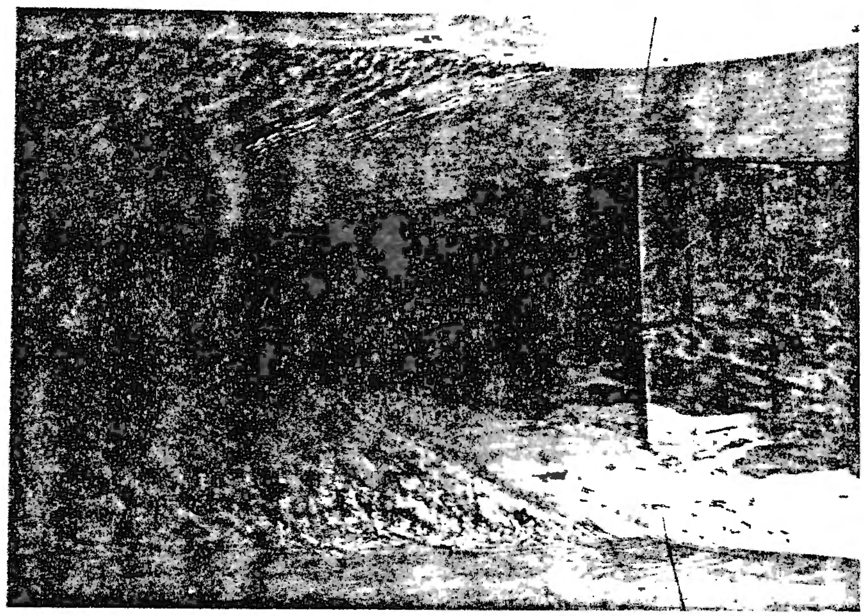


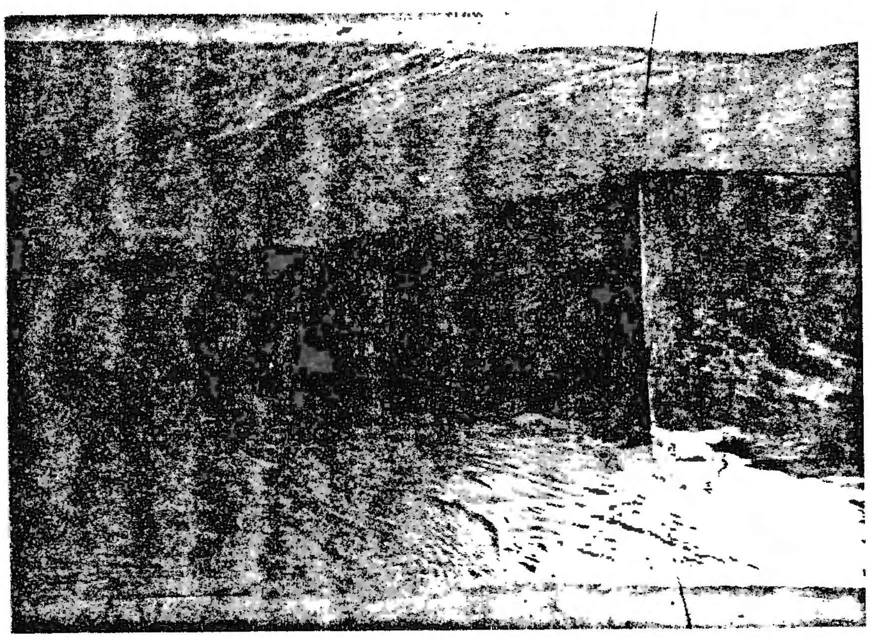
Figure 7. - Submergence characteristics.



a. Submergence less than 85 percent.

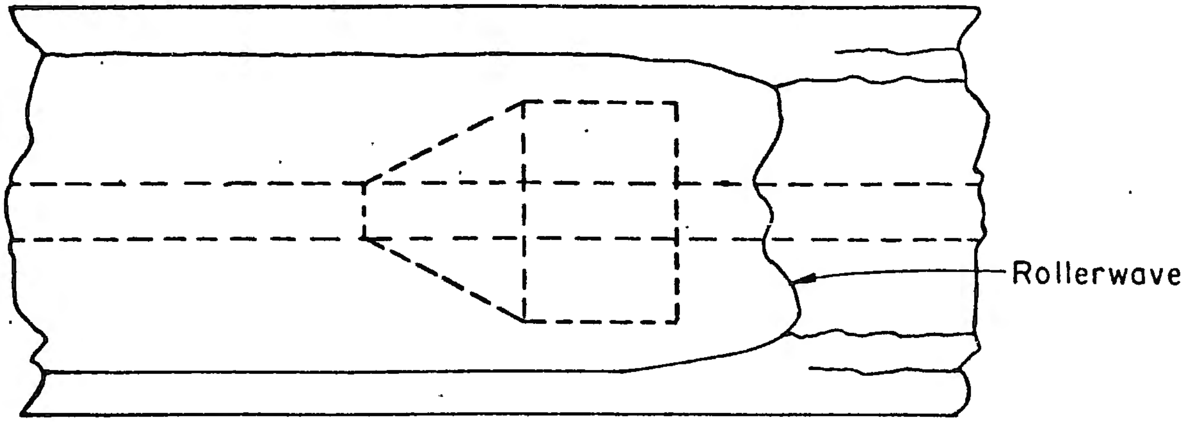


b. Submergence limit 85 percent.

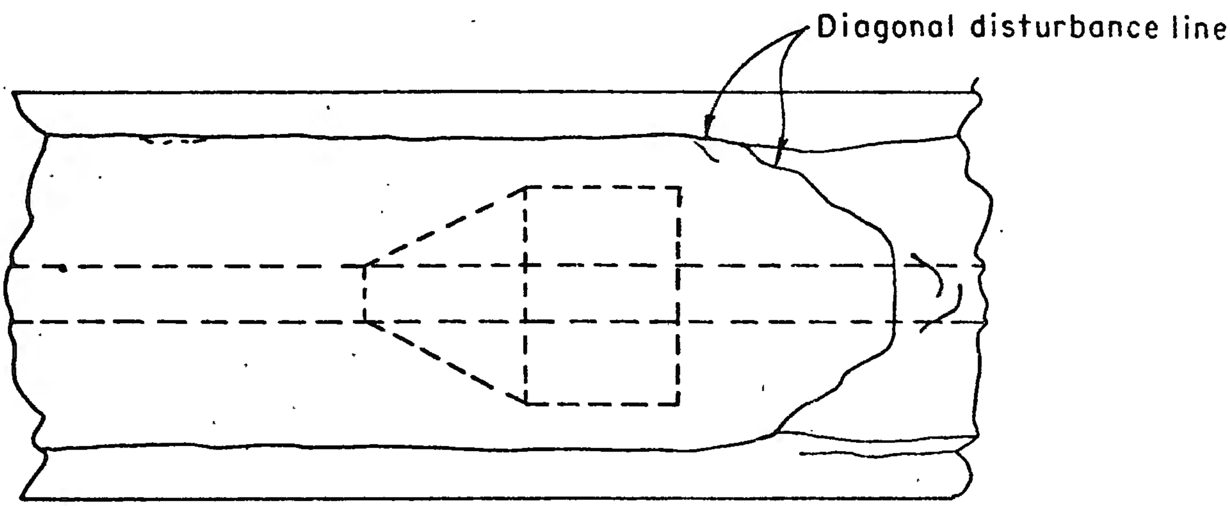


c. Submergence greater than 85 percent.

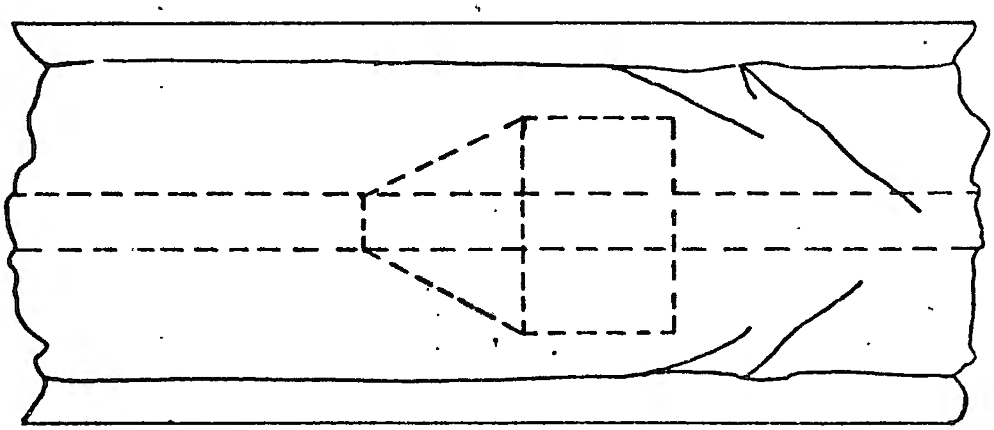
Figure 8. - Waveforms downstream of ramp flume - flow right to left.



(a) Submergence less than 85 percent



(b) Submergence limit 85 percent



(c) Submergence greater than 85 percent

Figure 9. - Sketches of waveforms downstream of ramp flume - flow from left to right.

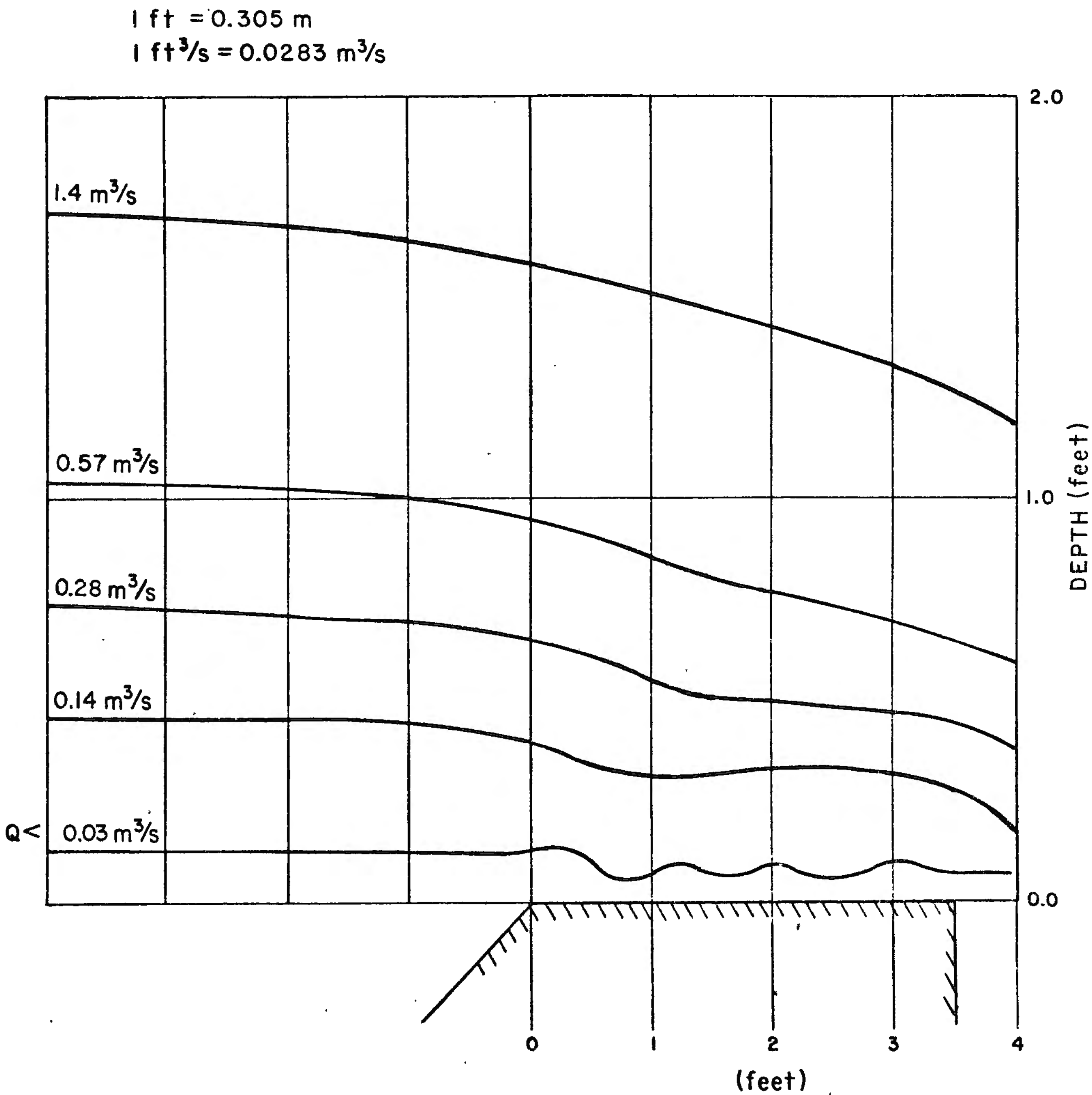


Figure 10. - Water surface profiles for various discharges.