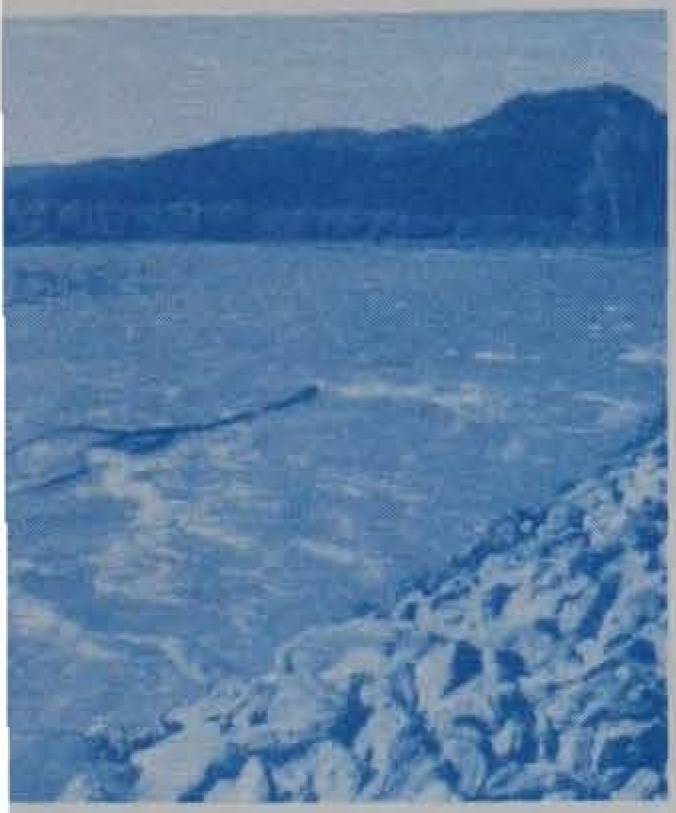

HYDRAULICS
LABORATORY

MISCELLANEOUS PAPER HL-92-5

RIPRAP RESISTANCE TESTS FROM A LARGE TEST CHANNEL

by

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December 1992

Final Report

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Civil Works Investigation Work Unit 32541

REPORT DOCUMENTATION PAGE

Form Approved c.3
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
December 1992

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Riprap Resistance Tests from a Large Test Channel

5. FUNDING NUMBERS
WU 32541

6. AUTHOR(S)
Stephen T. Maynord

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Waterways Experiment Station, Hydraulics
Laboratory, 3909 Halls Ferry Road, Vicksburg, MS
39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Miscellaneous Paper
HL-92-5

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers, Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Results from resistance tests conducted in a large test channel are in agreement with previous tests in rectangular tilting flumes. Flow resistance for riprap is best described by the Strickler equation, which can be derived from the power law equation for velocity profiles. The coefficient in Strickler's equation from the large test channel was 2.4 percent greater than from the rectangular tilting flumes. Results from this study suggest that the logarithmic equation is not valid for intermediate scale roughness. Riprap placed to simulate underwater placement had an n value 13 percent greater than riprap placed in dry conditions, where the rock surface is much smoother.

14. SUBJECT TERMS
Manning/Strickler equation
Resistance coefficients
Resistance equations
Riprap

15. NUMBER OF PAGES
26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

PREFACE

The study described herein was performed at the US Army Engineer Waterways Experiment Station (WES) during February-April 1991 for the Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Civil Works Research and Development Program. Funds were allocated under Civil Works Investigation Work Unit 32541, "Riprap Design and Cost Reduction: Studies in Near Prototype Size Laboratory Channel," under HQUSACE Program Monitor Mr. Thomas Munsey. This study was accomplished under the direction of Messrs. F. A. Herrmann, Jr., Director of the Hydraulics Laboratory (HL); R. A. Sager, Assistant Director, HL; and G. A. Pickering, Chief of the Hydraulic Structures Division (HSD), HL. The tests were conducted by Dr. S. T. Maynord, project engineer, and Mr. D. M. White, Spillways and Channels Branch (SCB), HSD, under the direct supervision of Mr. N. R. Oswalt, Chief, SCB. This report was written by Dr. Maynord and edited by Mrs. M. C. Gay, Information Technology Laboratory, WES.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	2.54	centimetres

RIPRAP RESISTANCE TESTS FROM A LARGE TEST CHANNEL

PART I: INTRODUCTION

Background

1. Resistance of flow over riprap boundaries is an important part of channel design and is used in determining water-surface elevations and velocities. A previous study* dealing with the flow resistance of riprap used data from several rectangular tilting flumes in which the riprap was placed on the bottom of the flume. Results from that study showed that flow resistance for relative depth d/D_{90} with values from 3 to 30 is best described by a power law rather than the commonly used logarithmic function. Here d is depth and D_{90} is the particle size of which 90 percent is finer by weight. Strickler's equation** was derived from the power law equation and resulted in the following, using particle size D_{90} in feet

$$n = 0.0360\ D_{90}^{1/6} \tag{1}$$

and using particle size D_{50} in feet

$$n = 0.0380\ D_{50}^{1/6} \tag{2}$$

where

n = Manning roughness coefficient

D_{50} = particle size of which 50 percent is finer by weight

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* Steve T. Maynord. 1991. "Flow Resistance of Riprap," Journal of Hydraulic Engineering, American Society of Civil Engineers, Vol 117, No. 6, pp 687-696.

** A. Strickler. 1923. "Contributions to the Question Concerning a Formula for Speed and the Roughness Numbers for Rivers, Channels and Culverts" ("Beitrage zur Frage der Geschwindigkeitformel und der Rauhigkeitszahlen fur Strome, Kanule und Geschlossene Leitungen"), Mitteilungen des Amtes fur Wasserwirtschaft, No. 16, Bern, Switzerland, pp 12-13 (in German).

Equations 1 and 2 are based on data from wide rectangular flumes having essentially two-dimensional flow.

Purpose and Scope

2. The objective of this study is to develop techniques for estimating flow resistance over riprap boundaries. The scope of this report is to compare flow resistance data collected in the trapezoidal channel in the Riprap Test Facility (RTF) at the US Army Engineer Waterways Experiment Station to the results of the data analysis from the rectangular tilting flume study.

PART II: EXPERIMENTAL INVESTIGATION

3. The RTF (Plate 1) is a large outdoor test channel having a 780-ft* length, four bendways, and a discharge range of 0 to 200 cfs. Two constant-speed pumps, C1 and C2, provide discharges of 52 and 49 cfs, respectively. Two variable-speed pumps, V1 and V2, provide maximum discharges of 42.5 and 48 cfs, respectively. The initial 203 ft of the RTF (Plate 2) was used in this study, which is a straight reach having a trapezoidal section with 12-ft bottom width. The channel has 1V:2H side slopes on both sides to sta 1+71 followed by an 8-ft-long transition on the left descending bank to a side slope of 1V:1.5H. The first 20 ft of the channel is covered with 6- to 12-in.-diam riprap to dissipate turbulence of flow leaving the pump discharge flume. The remainder of the straight reach was covered with riprap having the gradation shown in Plate 3. Plastic tubing was placed beneath the riprap at sta 0+47, 0+76, 1+05, 1+34, and 1+63 and was connected to a stilling well. The sensing end of the tube terminated at the channel center line. The channel cross section was surveyed at 11 sections and results are shown in Table 1. The elevations of the five survey points on the channel bottom were averaged at each cross section and are plotted in Plate 4. A least squares fit of the average bottom elevation data resulted in a bottom slope of 0.00289 ft/ft from sta 0+47 to 1+71.

4. Vertical velocity profiles were determined at sta 0+47, 1+05, and 1+63 to determine if the velocity profile was fully developed at sta 0+47, which was 27 ft from the large change in boundary roughness at sta 0+20. If the profile was not fully developed, data from sta 0+47 might be in error. Profiles were measured at the channel center line and 2 ft from each side of the center line. Results are shown in Plates 5-7 and 8-10 for discharges of 52 and 76 cfs, respectively. The velocity profile at sta 0+47 is not significantly different from those of the downstream stations, which means that data from sta 0+47 can be used in the analysis.

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* A table of factors for converting non-SI units of measurement to metric (SI) units is found on page 3.

PART III: ANALYSIS AND RESULTS

5. Water-surface elevations were measured for nine tests as shown in Table 2 and plotted in Plates 11 and 12. Note that the 75- and 76-cfs profiles exhibit a marked drop in water surface between sta 1+34 and 1+63. This is likely an effect of the downstream transition that was not significant at the lower discharges. Comparisons of observed versus computed water-surface elevations will not use sta 1+63 data for 75 and 76 cfs. All other profiles are typical backwater curves. Tests 1-8 represent dry-placed riprap having a relatively even surface. Test 9 was conducted with the riprap roughened to simulate the rougher surface typical of riprap placed underwater.

6. The cross-section data in Table 1 were used in the HEC-2 water—surface profile computation. For discharges other than 75 and 76 cfs, the observed water-surface elevation at sta 1+63 was used as the downstream starting water-surface elevation in the computations. For discharges of 75 and 76 cfs, the observed water-surface elevation at sta 1+34 was used as the downstream starting water-surface elevation. The n value that resulted in the best agreement between observed and computed water-surface elevation is shown in Table 2 along with the corresponding computed water-surface elevations. The average n value for Tests 1-8 was 0.0272. Using $D_{90} = 1.93$ in./12 = 0.161 ft from Plate 3 and the Strickler equation* results in

$$n = 0.0369\ D_{90}^{1/6} \tag{3}$$

Using $D_{50} = 1.4$ in./12 = 0.117 ft results in

$$n = 0.0389\ D_{50}^{1/6} \tag{4}$$

The coefficients in Equations 3 and 4 are about 2.4 percent greater than Equations 1 and 2 from Maynord.

7. The logarithmic equation for flow resistance is

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* Strickler, op. cit.

$$\left(\frac{8}{f}\right)^{1/2} = 5.75 \log\left(\frac{aR}{K_s}\right) \tag{5}$$

where

a = channel shape factor given by Hey*

R = hydraulic radius

K_s = equivalent sand grain roughness

and f is the Darcy friction factor defined as

$$f = \frac{8gRS}{V^2} \tag{6}$$

where

g = acceleration due to gravity

S = channel slope

V = channel velocity

The previous study found that the logarithmic equation (5) is not valid for intermediate scale roughness having $3 \le R/D_{90} \le 10$. The data in Table 3 were used to determine the least squares logarithmic equation

$$\left(\frac{8}{f}\right)^{1/2} = 4.20 \log\left(\frac{R}{D_{90}}\right) + 6.29 \tag{7}$$

As in the previous study, Student's t-test shows that the slope of Equation 7 of 4.20 is statistically different from the commonly accepted value of 5.75. Because of this difference, this study suggests that the logarithmic equations are not valid over the range of data used herein having $4.5 \le R/D_{90} \le 8.2$.

8. Comparison of results from Test 9 with the roughened riprap to Test 2 with the dry-placed riprap (Table 2) shows a (0.0306-0.0270)/0.0270 = 13 percent increase in n for the roughened riprap that was intended to simulate riprap placed underwater.

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* R. D. Hey. 1979. "Flow Resistance in Gravel-bed Rivers," Journal of the Hydraulics Division, American Society of Civil Engineers, Vol 105, No. HY4, pp 365-379.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

9. Results from resistance tests in the RTF are in agreement with results from tests in the rectangular tilting flumes.* The coefficient in Strickler's equation** from the RTF was 2.4 percent greater than the coefficient for the rectangular tilting flume.* Results from this study, similar to the previous study,* suggest that the logarithmic equation is not valid for intermediate scale roughness.

10. Riprap placed to simulate underwater placement had an n value 13 percent greater than riprap placed in dry conditions, where the rock surface is much smoother.

---

* Maynord, op. cit.

** Strickler, op. cit.

Table 1

Measured Cross Sections

Station 0+30	
X	Elevation
6.40	101.91
8.22	101.05
10.00	100.19
13.00	100.09
16.00	100.09
19.00	100.15
21.75	100.20
23.60	100.95
25.39	101.85

Station 0+47	
X	Elevation
6.41	101.98
8.25	101.17
10.00	100.21
13.05	100.10
16.10	100.11
19.15	100.07
22.20	100.24
23.98	101.16
25.83	101.92

Station 0+61.5	
X	Elevation
6.35	101.83
8.18	101.01
10.00	100.19
13.00	100.04
16.00	100.08
19.00	100.14
21.80	100.22
23.62	101.06
25.47	101.81

Station 0+76	
X	Elevation
6.39	101.87
8.19	101.00
10.00	100.14
13.00	100.03
16.00	99.99
19.00	100.02
22.00	100.07
23.82	100.90
25.59	101.83

Station 0+90.5	
X	Elevation
6.38	101.79
8.19	100.94
10.00	100.09
13.00	99.94
16.00	99.96
19.00	100.00
21.80	99.99
23.59	100.80
25.39	101.75

Station 1+05	
X	Elevation
6.38	101.78
8.20	100.95
10.00	100.08
13.00	100.00
16.00	99.93
19.00	100.00
22.00	100.08
23.80	100.95
25.63	101.76

Station 1+19.5	
X	Elevation
6.39	101.77
8.18	100.88
10.00	100.04
13.00	99.93
16.00	99.88
19.00	99.87
22.00	99.97
23.79	100.87
25.59	101.74

Station 1+34	
X	Elevation
6.43	101.75
8.23	100.87
10.00	99.94
13.00	99.83
16.00	99.80
19.00	99.80
21.80	99.91
23.65	100.68
25.48	101.47

Station 1+48.5	
X	Elevation
6.35	101.59
8.13	100.68
10.00	99.96
13.00	99.80
16.00	99.79
19.00	99.82
21.75	99.87
23.56	100.73
25.32	101.68

Station 1+63	
X	Elevation
6.39	101.64
8.16	100.70
10.00	99.92
13.00	99.79
16.00	99.77
19.00	99.80
22.00	99.89
23.79	100.78
25.63	101.58

Station 1+71	
X	Elevation
6.41	101.68
8.19	100.78
10.00	99.92
13.00	99.75
16.00	99.75
19.00	99.74
22.00	99.82
23.80	100.69
25.61	101.55

Note: Elevations are referenced to an arbitrary datum.
X = distance from left descending side of channel, feet.

Table 2

Observed Versus Computed Water-Surface Elevations

Test	Discharge	Best		Water-Surface Elevation* at Sta				
No.	cfs	n	Pumps	0+47	0+76	1+05	1+34	1+63
1	52.0	0.0278	C1	101.480	101.421	101.368	101.326	101.281
				101.480	101.420	101.360	101.330	101.280
2	48.0	0.0270	V2	101.394	101.342	101.286	101.246	101.199
				101.390	101.340	101.280	101.250	101.200
3	49.0	0.0272	C2	101.423	101.361	101.310	101.271	101.227
				101.420	101.370	101.300	101.270	101.230
4	42.5	0.0268	V1	101.299	101.236	101.183	101.143	101.098
				101.300	101.240	101.180	101.150	101.100
5	25.0	0.0277	V2	100.998	100.929	100.872	100.830	100.788
				101.000	100.930	100.870	100.830	100.790
6	25.0	0.0273	V1	100.987	100.918	100.861	100.818	100.776
				100.990	100.920	100.860	100.820	100.780
7	76.0	0.0268	C1, V2	101.797	101.740	101.688	101.660	101.566
				101.790	101.750	101.690	101.660	—
8	75.0	0.0272	C2, V1	101.783	101.727	101.678	101.643	101.548
				101.780	101.730	101.670	101.640	—
9	48.0	0.0306	V2	101.441	101.358	101.295	101.241	101.175
	Disturbed			101.430	101.370	101.290	101.240	101.180

---

* Elevations are referenced to an arbitrary datum. The first row of data for each test gives the observed elevations, and the second row gives the computed elevations.

Table 3

Derived Data

Test No.	Depth* ft	Hydraulic Radius R, ft	$\frac{R}{D_{90}}$	n (from Table 2)	$\left(\frac{8}{f}\right)^{1/2}$
1	1.35	1.10	6.84	0.0278	9.57
2	1.27	1.04	6.47	0.0270	9.76
3	1.29	1.06	6.59	0.0272	9.72
4	1.16	0.97	6.03	0.0268	9.72
5	0.85	0.74	4.60	0.0277	8.99
6	0.84	0.73	4.54	0.0273	9.10
7	1.67	1.31	8.15	0.0268	10.22
8	1.66	1.31	8.15	0.0272	10.07
9	1.28	1.05	6.53	0.0306	—

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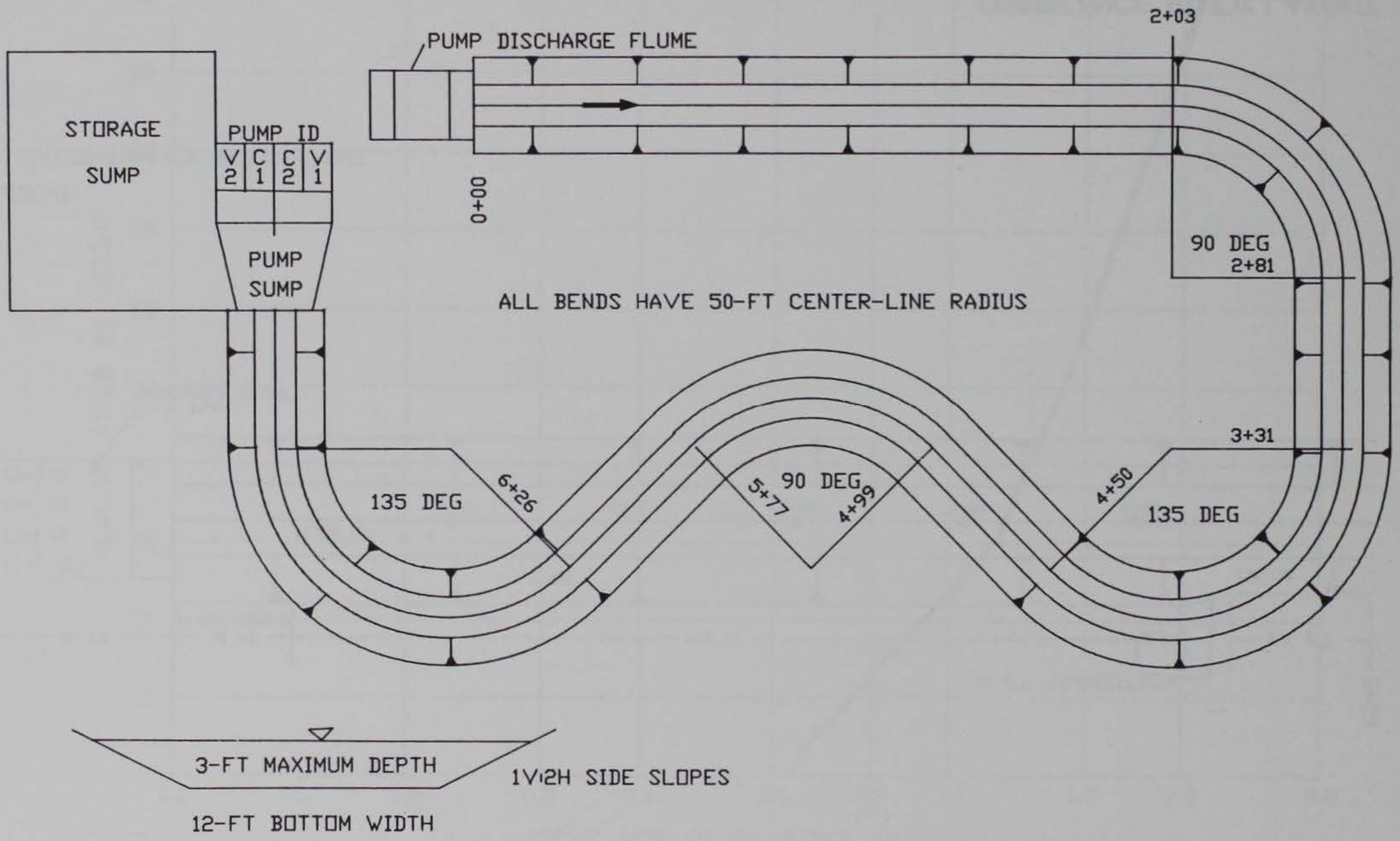
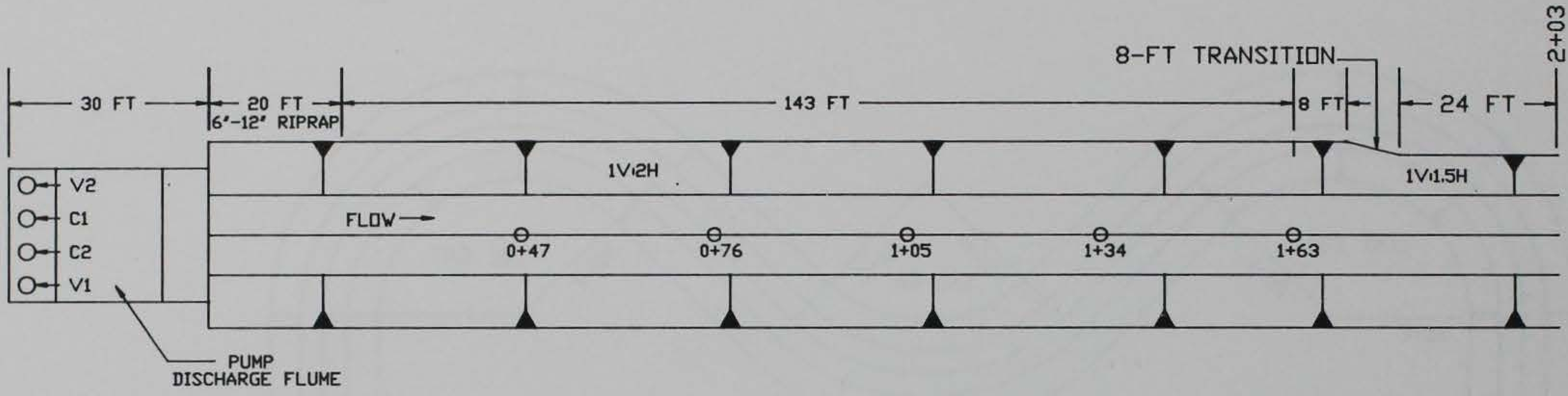
* Water-surface elevation - average bottom elevation at sta 1+05.



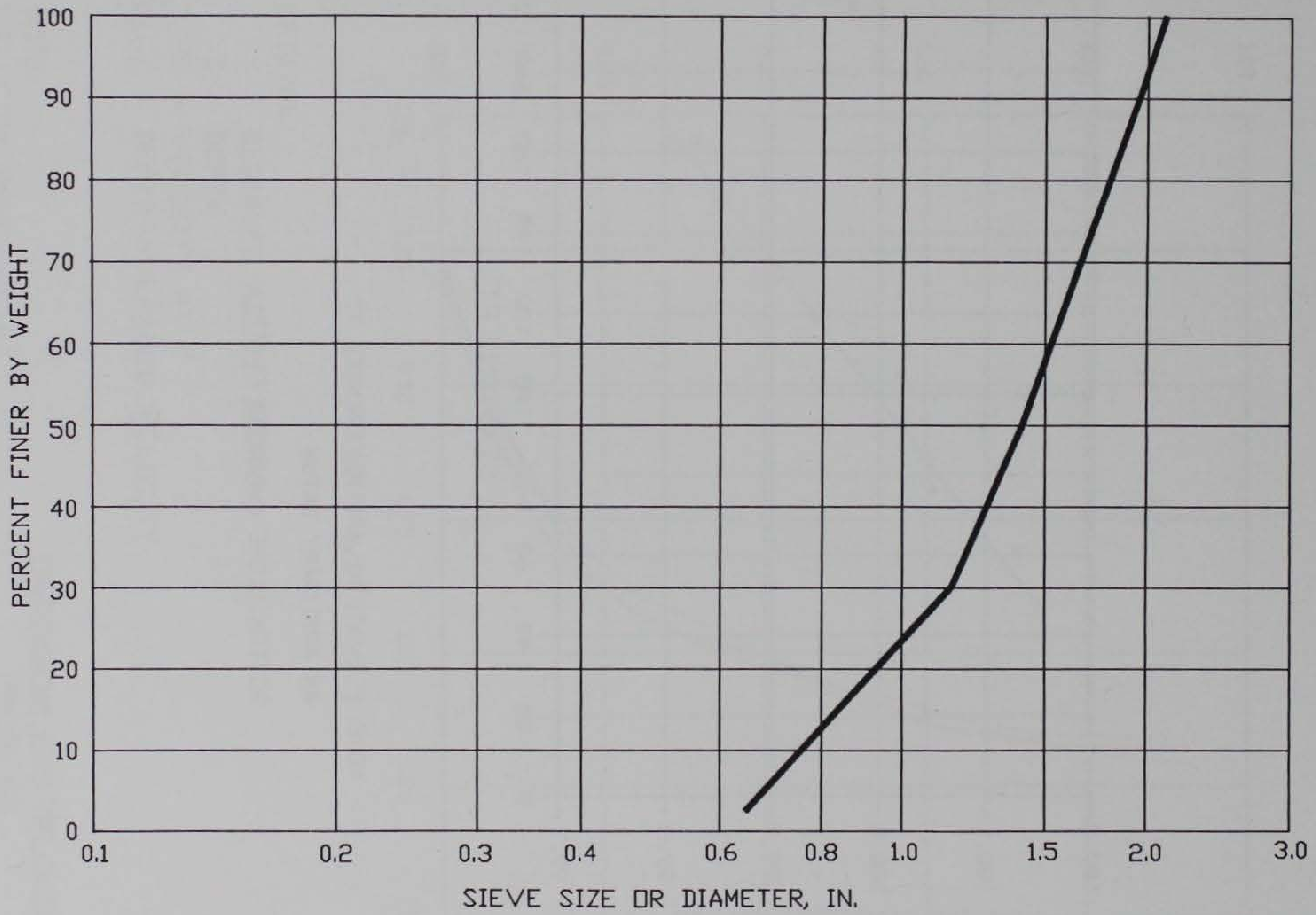
RIPRAP TEST FACILITY SCHEMATIC



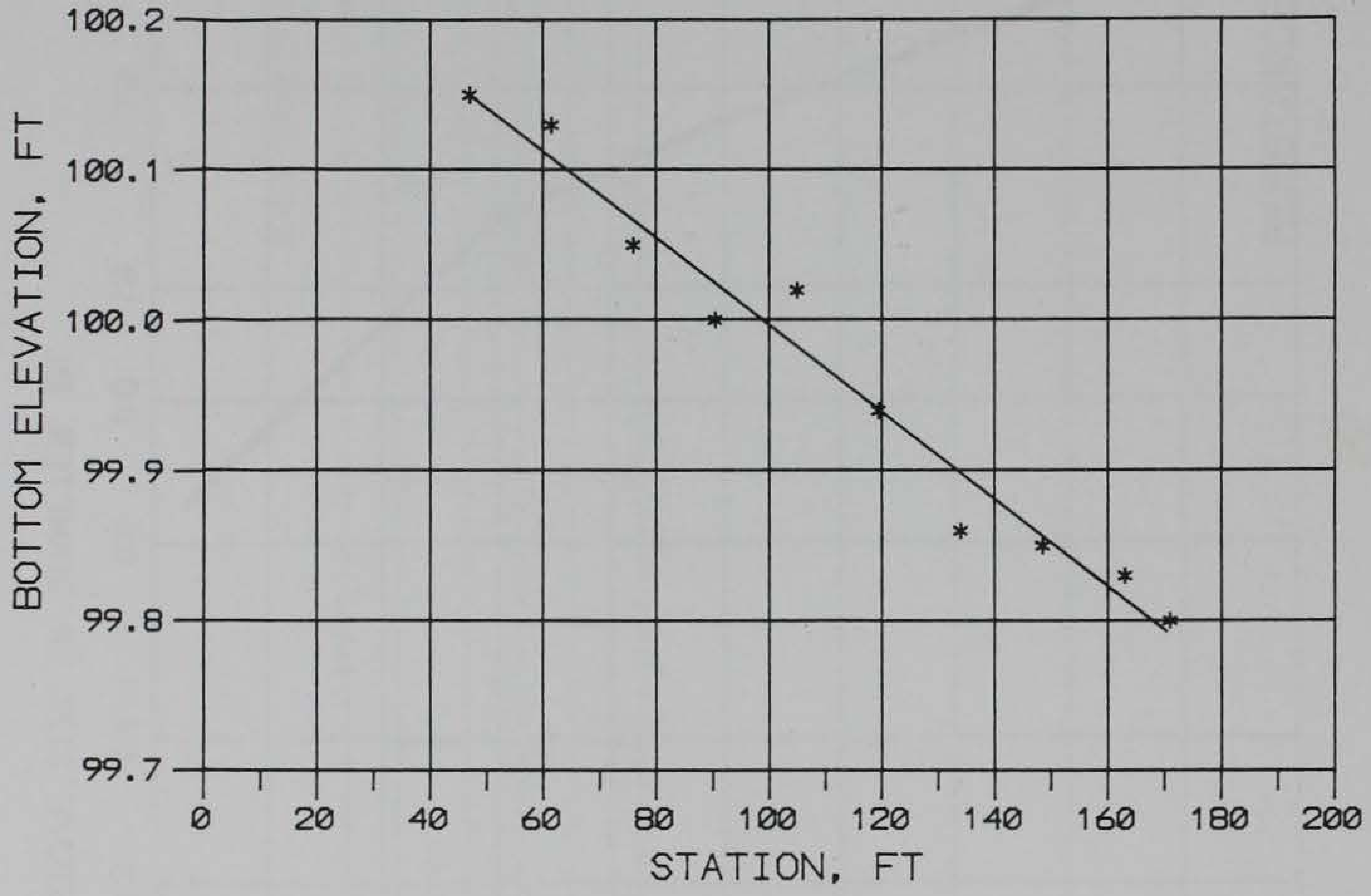
LEGEND:

o WATER-SURFACE MEASUREMENT

RESISTANCE STUDY LAYOUT



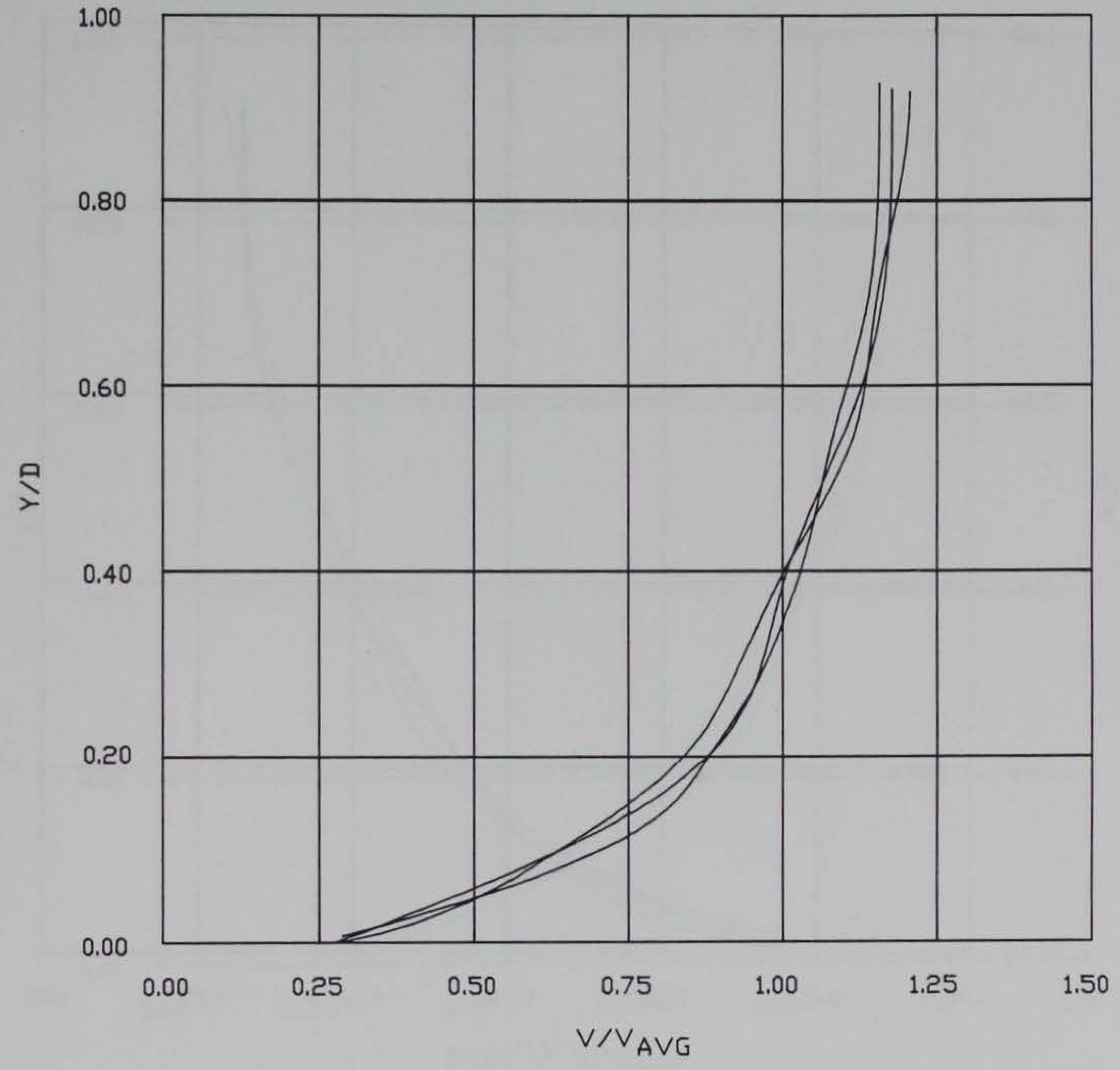
RIPRAP GRADATION 1



NOTE: ELEVATIONS ARE REFERENCED TO
AN ARBITRARY DATUM
BOTTOM SLOPE = 0.00289 FT/FT

CHANNEL BOTTOM SLOPE

PLATE 4



LEGEND:

Y = DISTANCE ABOVE BOTTOM

D = DEPTH

V = VELOCITY AT Y

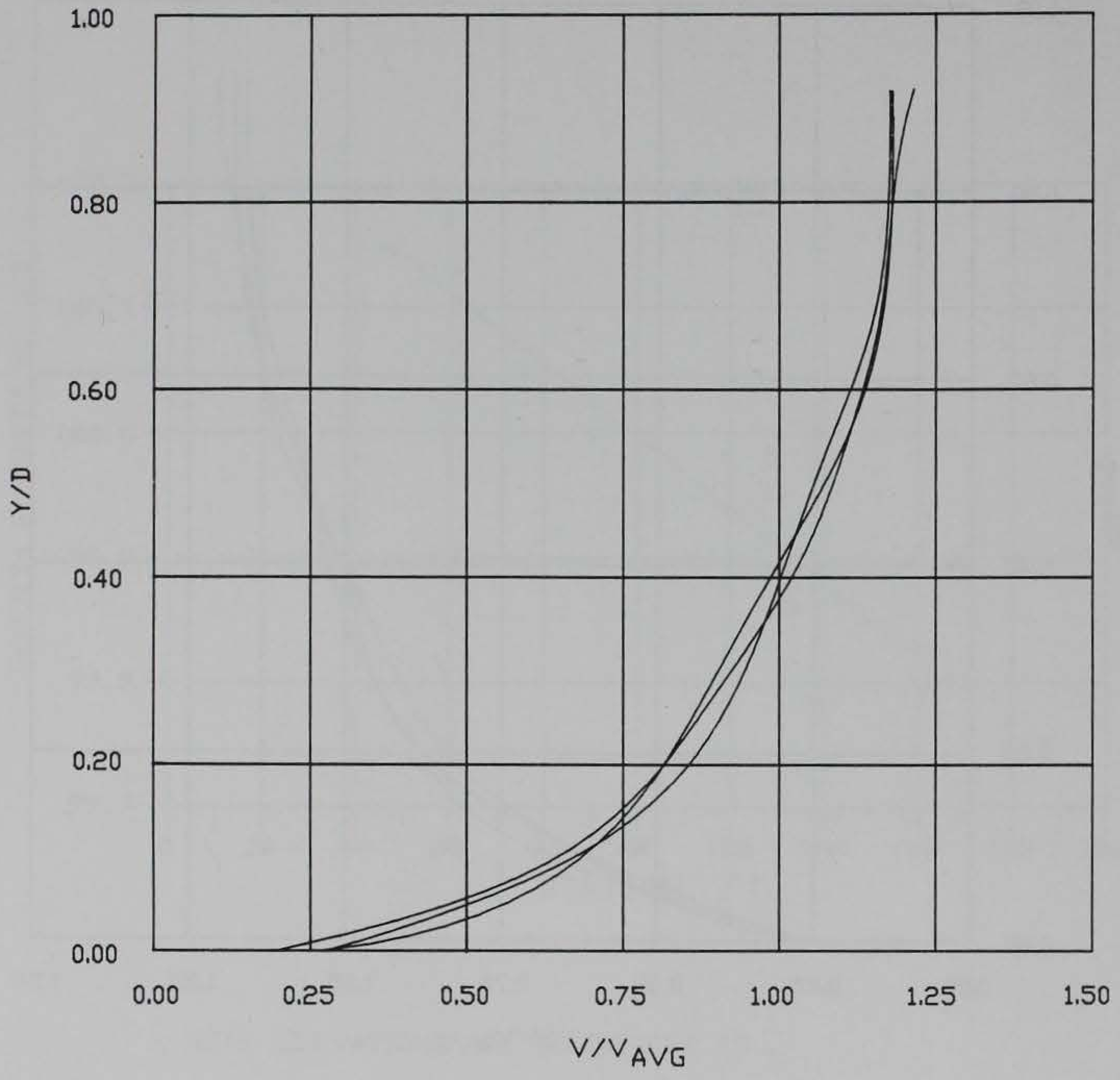
V_{AVG} = DEPTH-AVERAGED VELOCITY

NOTE:

VELOCITY PROFILES AT
CHANNEL CENTER LINE AND
2 FT ON EACH SIDE. CURVES
NOT LABELED DUE TO SIMILARITY

DIMENSIONLESS VELOCITY PROFILES

DISCHARGE 52 CFS
STATION 0+47



LEGEND:

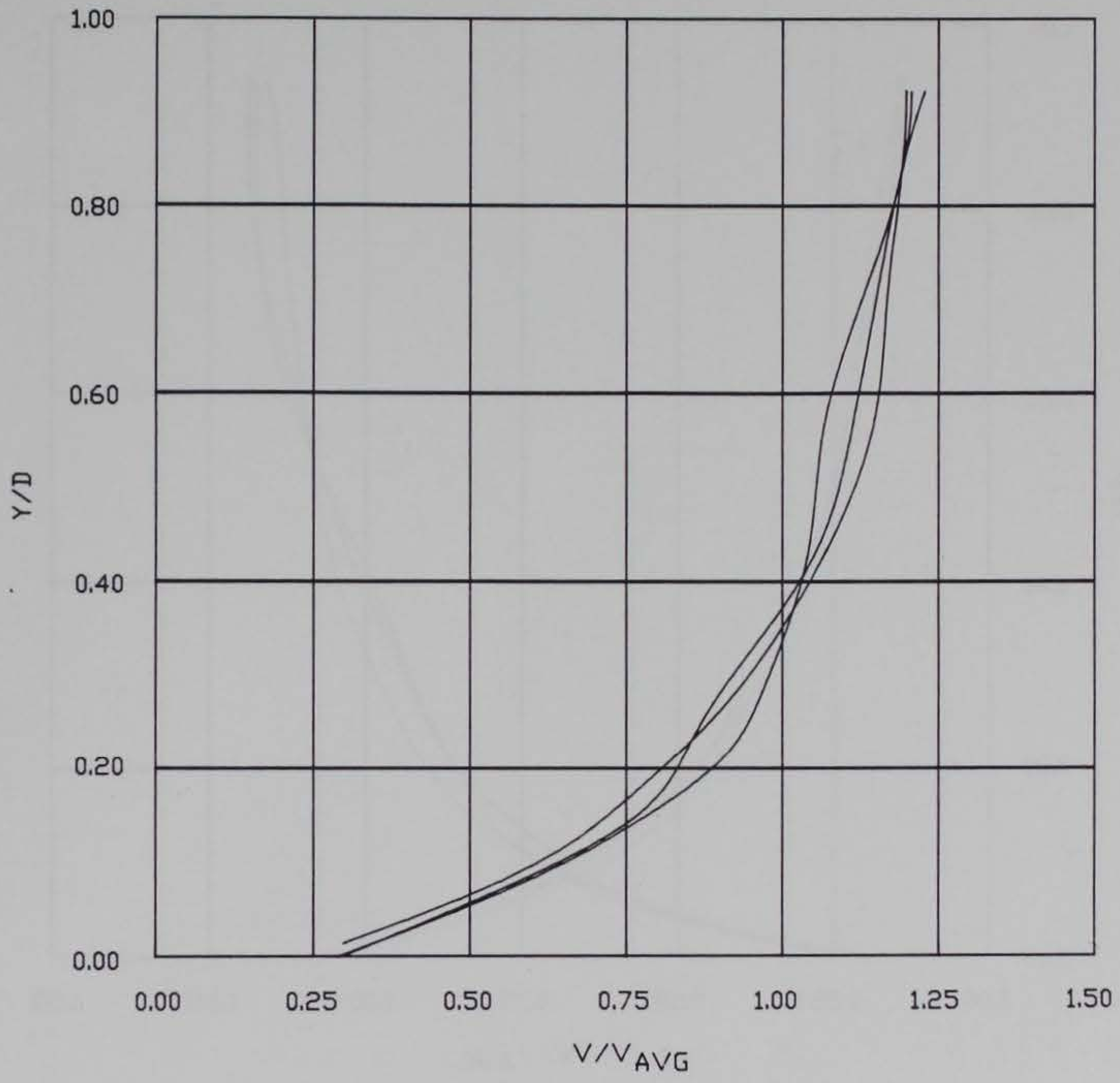
Y = DISTANCE ABOVE BOTTOM
D = DEPTH
V = VELOCITY AT Y
V_{AVG} = DEPTH-AVERAGED VELOCITY

NOTE:

VELOCITY PROFILES AT
CHANNEL CENTER LINE AND
2 FT ON EACH SIDE. CURVES
NOT LABELED DUE TO SIMILARITY

DIMENSIONLESS VELOCITY PROFILES

DISCHARGE 52 CFS
STATION 1+05



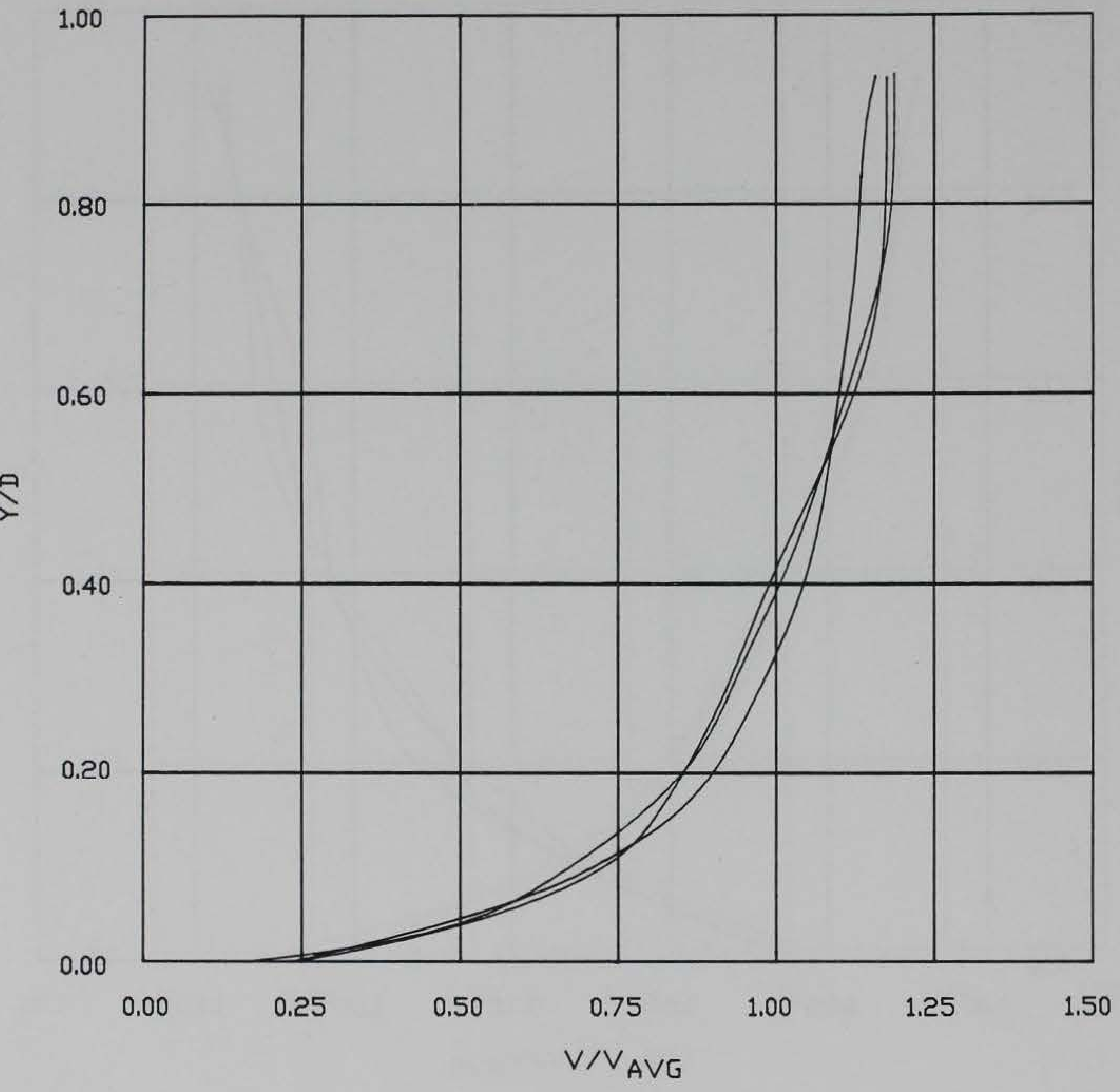
LEGEND:

Y = DISTANCE ABOVE BOTTOM
D = DEPTH
V = VELOCITY AT Y
V_{AVG} = DEPTH-AVERAGED VELOCITY

NOTE:
VELOCITY PROFILES AT
CHANNEL CENTER LINE AND
2 FT ON EACH SIDE. CURVES
NOT LABELED DUE TO SIMILARITY

DIMENSIONLESS VELOCITY PROFILES

DISCHARGE 52 CFS
STATION 1+63



LEGEND:

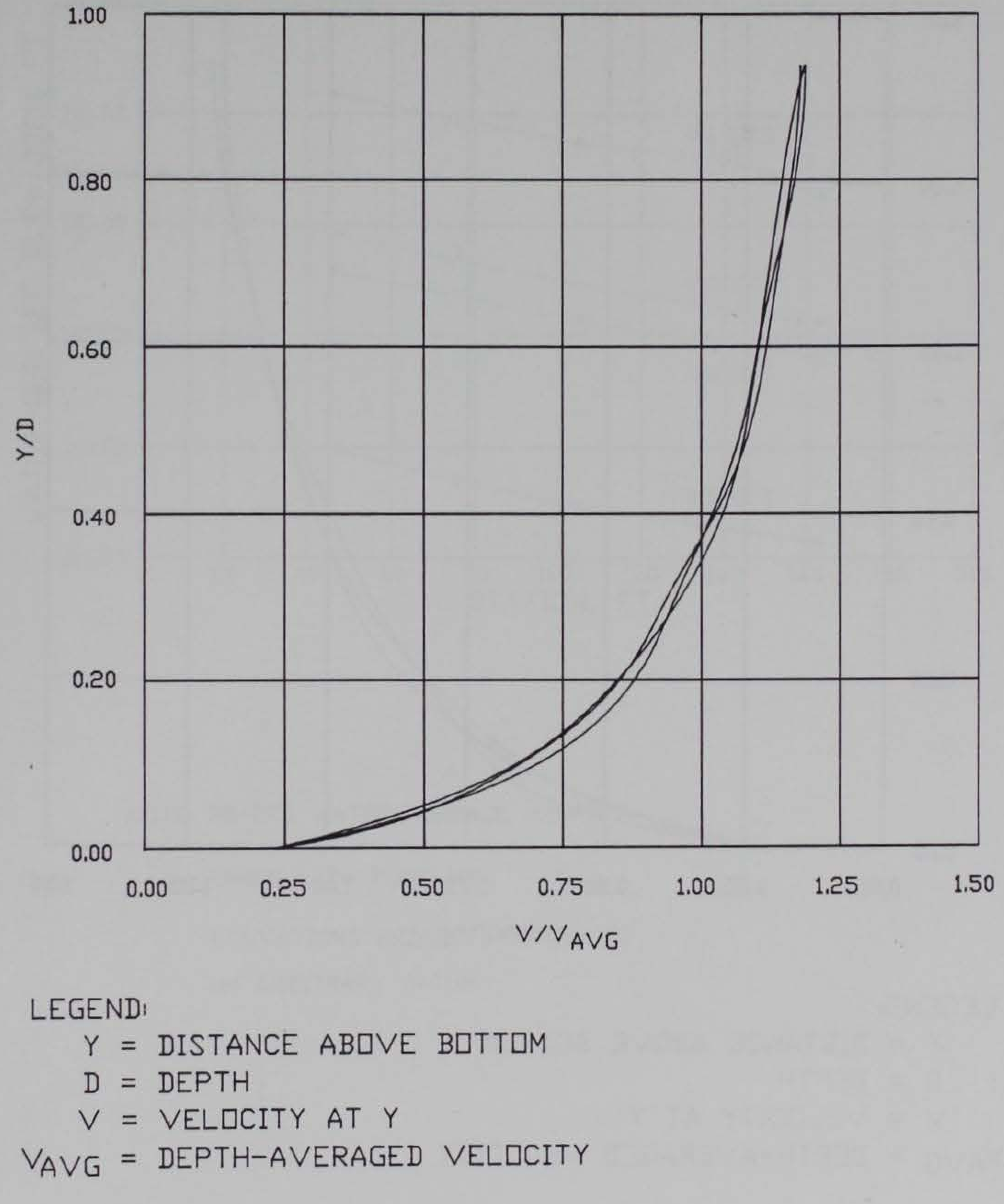
Y = DISTANCE ABOVE BOTTOM
D = DEPTH
V = VELOCITY AT Y
V_{AVG} = DEPTH-AVERAGED VELOCITY

NOTE:
VELOCITY PROFILES AT
CHANNEL CENTER LINE AND
2 FT ON EACH SIDE. CURVES
NOT LABELED DUE TO SIMILARITY

DIMENSIONLESS VELOCITY PROFILES

DISCHARGE 76 CFS
STATION 0+47

PLATE 8

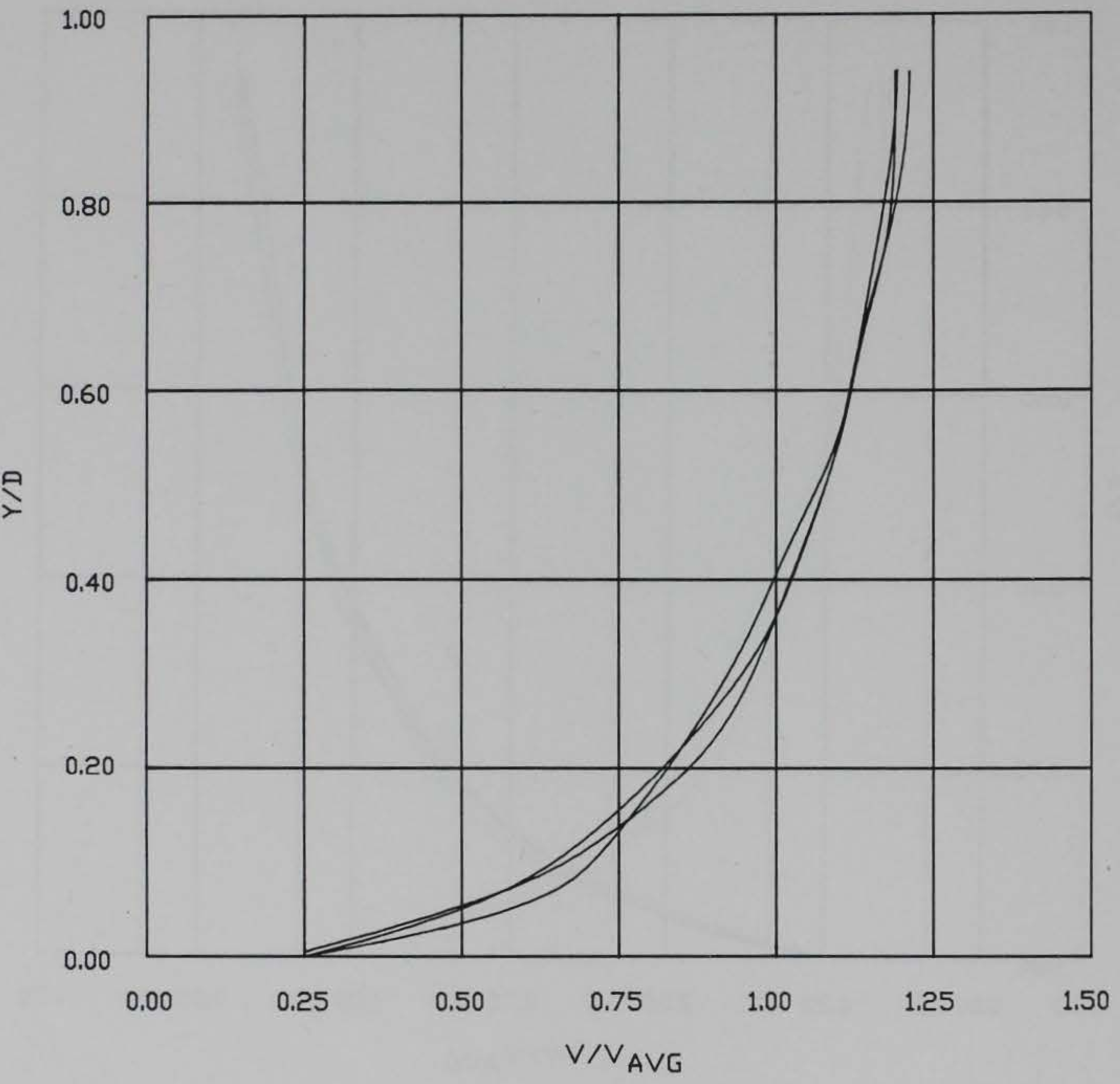


LEGEND:
Y = DISTANCE ABOVE BOTTOM
D = DEPTH
V = VELOCITY AT Y
V_{AVG} = DEPTH-AVERAGED VELOCITY

NOTE:
VELOCITY PROFILES AT
CHANNEL CENTER LINE AND
2 FT ON EACH SIDE. CURVES
NOT LABELED DUE TO SIMILARITY

DIMENSIONLESS VELOCITY PROFILES

DISCHARGE 76 CFS
STATION 1+05



LEGEND:

Y = DISTANCE ABOVE BOTTOM
D = DEPTH
V = VELOCITY AT Y
V_{AVG} = DEPTH-AVERAGED VELOCITY

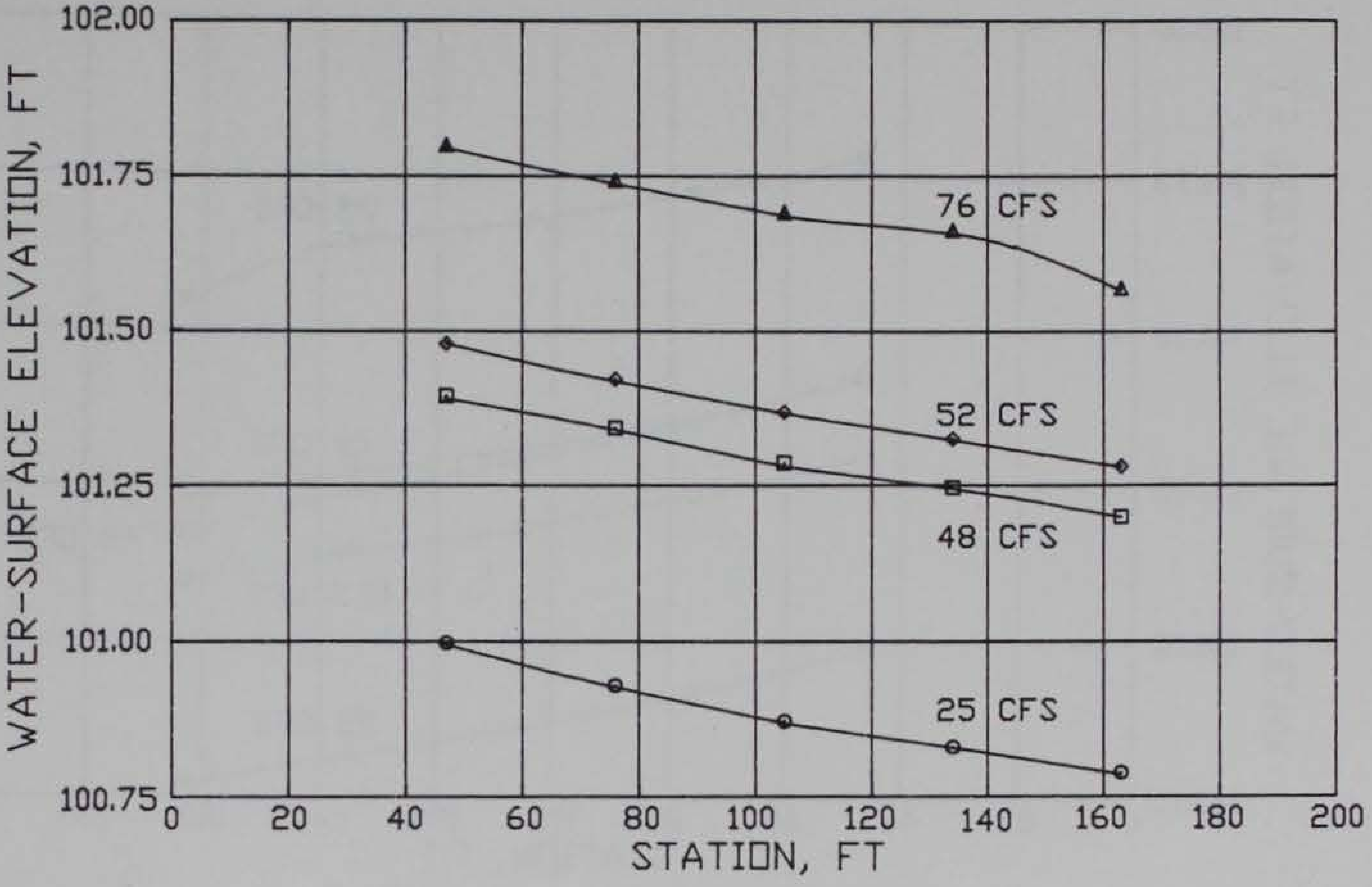
NOTE:

VELOCITY PROFILES AT CHANNEL CENTER LINE AND 2 FT ON EACH SIDE. CURVES NOT LABELED DUE TO SIMILARITY

DIMENSIONLESS VELOCITY PROFILES

DISCHARGE 76 CFS
STATION 1+63

PLATE 10



NOTE: 25-CFS WATER-SURFACE PROFILE

TAKEN WITH PUMP V2

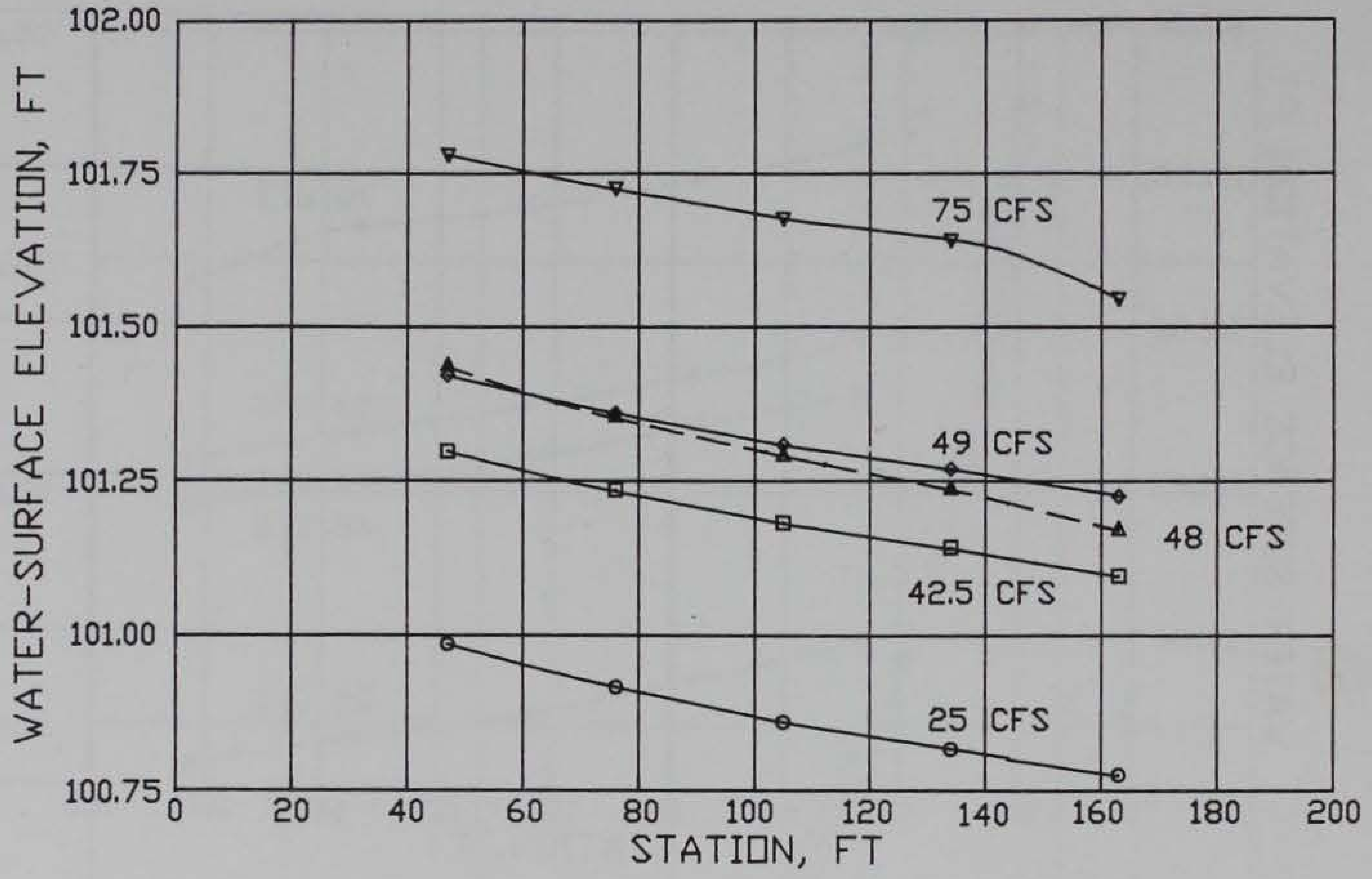
ELEVATIONS ARE REFERENCED TO

AN ARBITRARY DATUM

WATER-SURFACE PROFILES

DISCHARGE 25, 48, 52, AND 76 CFS

PLATE 11



NOTE: 25-CFS WATER-SURFACE PROFILE
TAKEN WITH PUMP V1.
48-CFS WATER-SURFACE PROFILE
TAKEN WITH RIPRAP SURFACE ROUGHENED
TO SIMULATE UNDERWATER PLACEMENT.
ELEVATIONS ARE REFERENCED TO
AN ARBITRARY DATUM

WATER-SURFACE PROFILES

DISCHARGE 25, 42.5, 48, 49, AND 75 CFS