ON THE DESIGN OF AN ARMORPLATED STILLING BASIN FOR A CANTILEVERED OUTLET ON THE TURKEY CREEK WATERSHED, COLORADO

By

G. L. Smith

TO

BUREAU OF PUBLIC ROADS

U. S. DEPARTMENT OF COMMERCE

through
Colorado State University Research Foundation
Fort Collins, Colorado

November, 1957

CER57GLS33

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1. INTRODUCTION: The basic problem involved is that of preventing water from entering a spring house located in the drainage way of a cantilevered pipe culvert. (See Fig. 1) The pipe culvert is located near Schaffer's Crossing on U. S. Highway 285. It provides cross-drainage for runoff from approximately 20 acres of mountainous terrain in the Turkey Creek Watershed.

The design problem is to determine the characteristics of a stilling basin at the culvert outlet, which will provide a simple and economical method of dissipating the kinetic energy of the freely-falling water jet and will provide a means of diverting the water flow away from the spring house into its former natural channel. The design is to be based on data determined by model study of scour control of flow from cantilevered pipe culverts at Colorado State University. The characteristics determined on the basis of the data are tentative and subject to change as continuing experimental study makes further data available. The stilling basin will be a pre-shaped scour hole armorplated by graded aggregate.

A pictorial description of the general conditions existing upstream and downstream of the pipe culvert is depicted by Figs. 2 and 3.

A diagram giving the details of the armorplated stilling basin is shown in Fig. 4. A diagram similar to Fig. 4 was provided for the Colorado State Highway Department.

2. DESIGN PROBLEM: To determine the design characteristics of a pre-shaped stilling basin armorplated by graded riprap.

3. DESIGN INFORMATION - GIVEN

Hydraulic Characteristics - The following hydraulic characteristics were provided by the Region Nine Office of the Bureau of Public Roads, and by the Colorado State Highway Department:

Q discharge in c.f.s.

25 cfs.

S_o slope of the c.m. pipe in ft/ft

5 per cent

L Length of pipe in ft

130 ft

n Manning's coefficient of roughness

0.024

H height of c.m. pipe invert above original ground

8.0 ft (estimated)

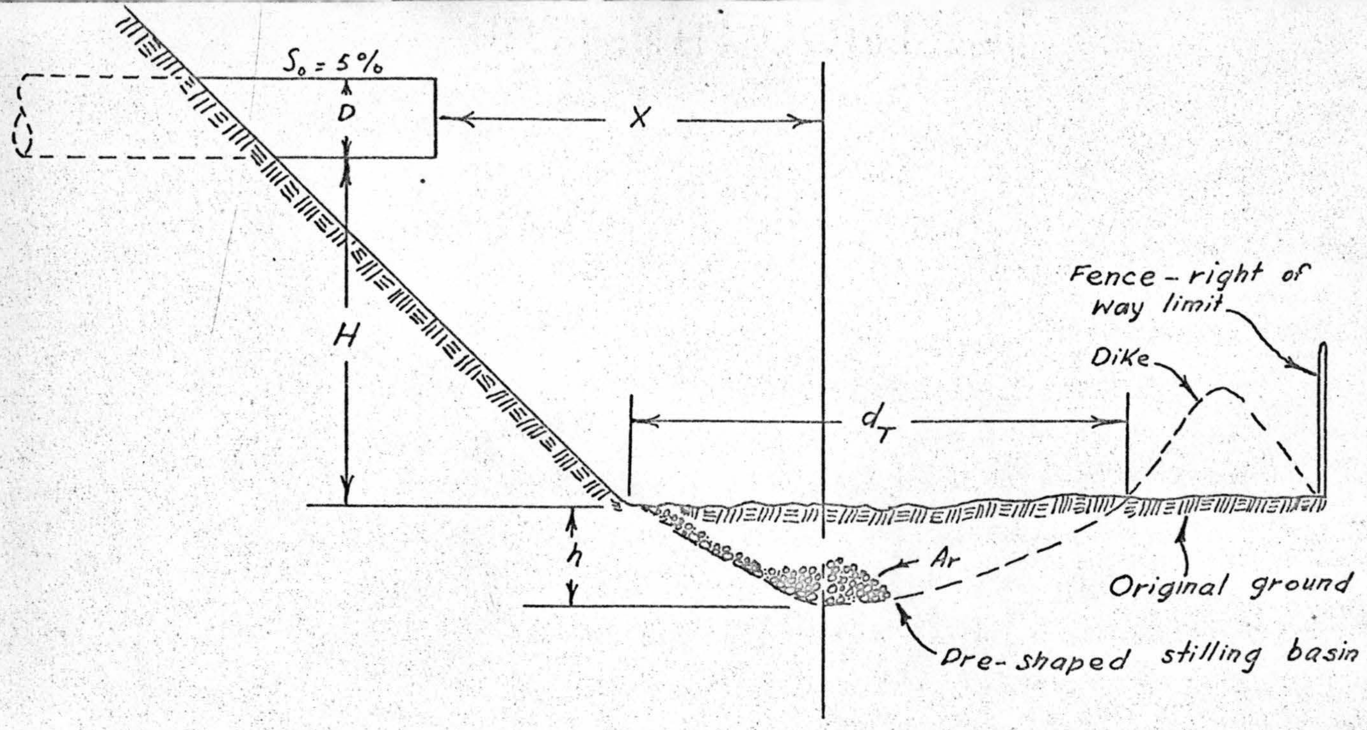
D diameter of pipe in in.

24 in.

Sediment Analysis - A sediment analysis of the subgrade material was made by the field laboratory of the Colorado State Highway Department. A mechanical sieve analysis of two random samples of subgrade material was as follows:

Sample No. 1		Sample No. 2	
Size of Sieve Openings in.	Per cent Passing	Size of Sieve Openings in.	Per cent Passing
2 1/2	100	2 1/2	100
3/4	93.7	3/4	98.1
1/2	92.7	1/2	91.0
3/8	85.8	3/8	79.8
No. 4 [1]	63.4	No. 4	51.8
No. 10	41.1	No. 10	32.0
No. 200	10.5	No. 200	5.7

1. Standard Tyler Sieve Mesh. Number.



Schematic diagram showing the required design characteristics of an armorplated stilling basin below a culvert outlet on the Turkey Creek Watershed.

4. DESIGN INFORMATION - REQUIRED

Stilling Basin Characteristics - The foregoing sketch illustrates the design characteristics needed to construct an armorplated stilling basin. The design characteristics required are:

d_T diameter of the stilling basin at the original ground level in ft

h the maximum depth of the basin measured from the original ground surface in ft

A_r quantity of armorplate -- graded aggregate with minimum size equal to maximum size of bed material -- in cu. yds

X distance of maximum depth of stilling basin from end of pipe outlet in ft.

Stilling Basin Performance - Flow from the stilling basin is to be transverse to the incoming flow, which will necessitate a dike downstream from the impinging jet. Furthermore, because of drainage along the toe of the roadway embankment, the stilling basin shall permit entry of this water and shall provide adequate control for the outflow into a properly designed drainage ditch.

5. PROBLEM ANALYSIS

Pipe Flow - To determine the design criteria for the stilling basin, it is essential that the flow conditions at the pipe outlet be examined.

According to model studies of culvert pipe flow, there are several possible flow conditions in the culvert at maximum discharge. For design purposes, it will be assumed that the flow is steady and uniform for a) normal depth of flow d_n less than critical depth d_c at pipe outlet, and for b) pipe flowing full.

Critical depth d_c is determined from Fig. 5 on the basis of the following calculation:

$$\frac{Q}{D^{5/2}} = \frac{25}{(2)^{5/2}} = \frac{25}{5.65} = 4.43$$

For $Q/D^{5/2} = 4.43$, Fig. 5 gives a value of $d_c/D = 0.88$; $\underline{d_c = 1.76 \text{ ft.}}$

On the basis of Manning's formula

$$Q = \frac{1.486}{n} R^{2/3} S_o^{1/2} A$$

It is known that for normal depth d_n

$$\frac{Q \cdot n}{(1.486) S_o^{1/2}} = AR^{2/3}$$

Therefore, by plotting depth of flow d_n in the pipe against $AR^{2/3}$ on log-log scales, a value for d_n can be determined. Fig. 6 shows the variation of log $AR^{2/3}$ with a log d and was plotted from points given in the following table.

Table 1. Values of $AR^{2/3}$ for depth of flow d for a pipe of 24-in. diameter.[1]

d	$\frac{d}{D}$	$\frac{A}{D^2}$	A	$\frac{R}{D}$	R	$R^{2/3}$	$AR^{2/3}$
1.0	0.5	0.3927	1.5708	0.2500	0.5000	0.630	0.99
1.2	0.6	.4920	1.9680	.2776	.5552	.676	1.33
1.4	0.7	.5872	2.3488	.2962	.5924	.706	1.66
1.6	0.8	.6736	2.6944	.3042	.6084	.718	1.93
1.8	0.9	.7445	2.9780	.2980	.5960	.708	2.10

For

$$Q = 25 \text{ c.f.s.}$$

$$n = 0.024$$

$$S_o = 0.05$$

We have

$$\frac{Qn}{1.486\, S_o^{1/2}} = \frac{(25)\,(0.024)}{(1.486)\,(0.05)^{1/2}} = 1.8$$

From Fig. 6 for $AR^{2/3} = 1.8$ we find that $\underline{d_n = 1.49 \text{ ft}}$

Based on an analysis of the jet trajectory, the distance from the pipe outlet X_B to the point of impingement on the original bed level is given by

1. Values of A/D^2 and R/D for d/D values are from TABLE 103 of "Hydraulic of Steady Flow in Open Channels" by Woodward and Posey. John Wiley, New York, 1941.

$$X_B = \frac{V_o}{g}\left[-\alpha + \sqrt{\alpha^2 + \frac{2gy}{V_o^2}(\mathrm{Cos}\ \alpha\ )}\right] \tag{1}$$

Where V_o is the jet velocity at pipe exit

α is the angle (in radians) the pipe culvert makes with the horizontal, or the slope S_o for very small angles.

Thus, for normal depth d_n at the outlet, we have

d_n = 1.49 ft; $\frac{d}{D}$ = 0.75 and from Fig. 7 $\frac{A}{D^2}$ = 0.632

A = area of jet at the exit

= $(2)^2$ (0.632) = (4) (0.632) = 2.528 ft^2.

$$V_o = \frac{Q}{A} = \frac{25}{2.528} = 9.89 \text{ fps}$$

= 0.05

and cos α = 1.0

For if α is expressed in radians, then

$$\cos \alpha = 1 - \frac{\alpha^2}{2} + \frac{\alpha^4}{4} - \frac{\alpha^6}{6} + \cdots$$

Which is approximately 1.0 when α = 0.05.

Solving Eq. 1 for X_B, we have

$$X_B = \frac{(9.86)^2}{32.2}\left[-0.05 + \sqrt{0.0025 + \frac{(2)\ (32.2)\ (8)}{(9.89)^2}}\right] \tag{2}$$

$$X_B = 3.02\left[-0.05 + \sqrt{0.0025 + 5.27}\right]$$

$$= (3.02)\ (2.25) = \underline{6.80}\ \text{ft.}$$

For pipe full flow at the outlet, we have

d = D = 1.9

$\frac{d}{D}$ = 0.95; $\frac{A}{D^2}$ = 0.771 from Fig. 7.

A = (4) (0.771) = 3.084

$$V_o = \frac{25}{3.084} = 8.1 \text{ fps}$$

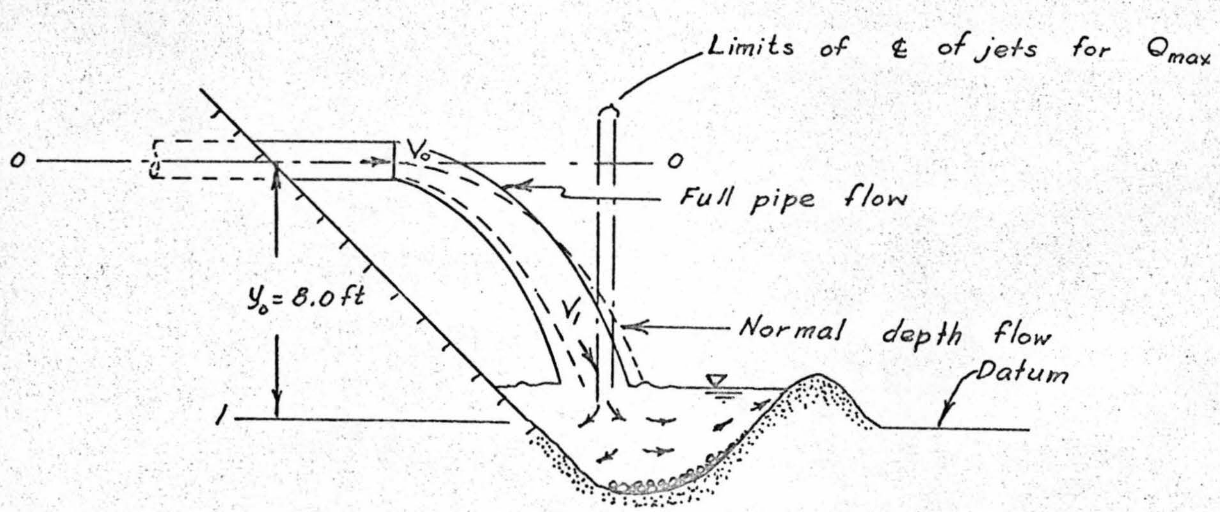
therefore

$$X_B = \frac{(8.1)^2}{32.2}\left[-0.05 + \sqrt{0.0025 + \frac{(2)\,(32.2)\,(8)}{(8.1)^2}}\,\right]$$

$$= (2.04)\,(-0.05 + \sqrt{0.0025 + 7.85}\,)$$

$$= (2.04)\,(2.75) = \underline{5.6\ \text{ft}}$$

Impinging Water Jet - The velocity of the impinging jet at the tailwater surface is determined by means of Bernoulli's equation.



In the foregoing sketch,

$$\frac{V_0^2}{2g} + \frac{p_0}{\gamma} + y_0 = \frac{V_1^2}{2g} + \frac{p_1}{\gamma} + y_1$$

or

$$\frac{V_0^2}{2g} + 0 + 8 = \frac{V_1^2}{2g} + 0 + 0$$

Solving for V_1, we have, for maximum exit velocity,

$$V_1 = \sqrt{V_0^2 + (2g)(8)} = \sqrt{(9.89)^2 + (64.4)\,(8)}$$

$$= \sqrt{97.8 + 514.2} = \sqrt{613} = 24.8 \text{ fps.}$$

Solving for the momentum flux M_F of the jet at the tailwater surface, we have

$$M_F = \rho_w QV = (1.94)\ (25)\ (24.8)$$

$$= 1200 \text{ lb}$$

From a log-normal plot (see Fig. 8) of a sediment analysis of the bed material, we can determine values for the sediment characteristics d_n and from Fig. 8 obtain

$$d_n = 3.35 \text{ mm}$$

$$= 11 \times 10^{-3} \text{ ft}$$

$$\sigma_d = 10.35 \text{ mm} - 3.35 \text{ mm} \quad (d_{84.1} - d_{50}).$$

$$= 7.0 \text{ mm}$$

$$= 23 \times 10^{-3} \text{ ft}$$

From Fig. 9 obtain, for $d_n = 3.35$ mm,

$$W_m = 24 \text{ cm/sec.}$$

$$= 0.79 \text{ f.p.s.}$$

Solving the parameter

$$\frac{M_F}{\rho_s W_m^2 \sigma_d b}$$

we have, by assuming $\rho_s = 2.65$ (sp.gr. of sedimentary rock) and $b = 1.0$ (tailwater depth),

$$\frac{(1.94)\ (25)\ (24.8)}{(2.65)\ (0.79)^2\ (23)\ (10^{-3})\ (1)} = 3.15 \times 10^4$$

Therefore, from Fig. 10, for

$$\frac{M_F}{\rho_s W_m^2 \sigma_d b} = 3.15 \times 10^4$$

obtain

$\beta = 2.50$

Solving the parameter

$$\frac{M_p}{\rho_s W_m^2 \sigma_d^2}$$

we have

$$\frac{1200}{(2.65)(0.79)^2 (23)^2 (10^{-3})^2} = 1.37 \times 10^6$$

Therefore, from Fig. 11, for $\frac{M_p}{\rho_s W_m^2 \sigma_d^2} = 1.37 \times 10^6$

obtain

$$\frac{h^*_{100} + \beta b}{(AH)^{1/3}} = 3.59$$

Substituting for β, b, A and H the values

$\beta = 2.50$

$b = 1.0$ ft

$A = 3.1416$ ft^2 (Area of full pipe flow).

$H = 9.0$ ft

we have

$$h^*_{100} = (3.59) \left[(3.1416 (9)\right]^{1/3} - (2.50 (1.0) = 8.41 \text{ ft.}$$

6. <u>DESIGN OF ARMORPLATED STILLING BASIN</u>

Solving for h^*, where h^* is the cube root of the volume of stilling basin $\sqrt[3]{V_s}$, obtain

$$h^* = (0.63)\ (h^*_{100}) = (0.63)\ (8.41) = 5.3 \text{ ft.}$$

<u>Note</u>: $h^* = (0.63)\ (h^*_{100})$ was determined on the basis of experimental studies, the distance X from the pipe outlet to point of maximum depth of stilling basin is given by

$$X = X_B + 0.6\, h^* + (b - 0.25H)$$

where $(b-0.25H)$ is omitted when b is less than $0.25H$. For the conditions given $0.25H = 2.00$; therefore, $b - 0.25H$ is to be omitted.

Solving

$$X = 6.76 + (0.6)(5.30) = 9.94 \text{ ft } (d_n < d_c)$$

and

$$X = 5.6 + (0.6)(5.30) = 8.78 \text{ ft } (d \doteqdot D)$$

Likewise from experimental studies it has been found that

$$d_T = 2.5\, h^* \quad \text{(see sketch on page 6)}$$

$$h = 0.5\, h^* \quad \text{(see sketch on page 6)}$$

Therefore, by substitution

$$d_T = (2.5)(5.3) = \underline{13.25 \text{ ft}}$$

$$h = (0.5)(5.3) = \underline{2.65 \text{ ft}}$$

The amount of graded gravel to be used as armorplating is given by

$$\%\, A_r = \frac{Var}{Vs}(100)$$

where V_{ar} is the volume of armorplate

V_s is the volume of scour at $T = 100$ hrs in the model.

Again experimental tests have shown that A_r should be about 8%.

In terms of h_{100}

$$V_{AR} = (0.08)\ V_s = (0.08)\ (h^*_{100})^3$$

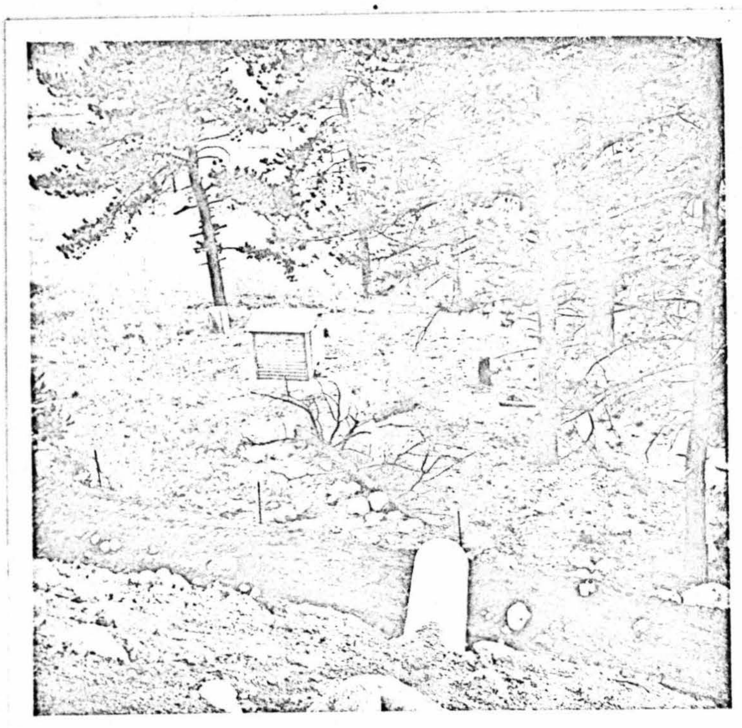
$$V_{AR} = (0.08)\ (8.27)^3 = (0.08)\ (566)$$

$$= 45.3\ ft^3 = \underline{1.68\ cu.\ yds}$$

The recommended gradation of the armorplate was as follows:

Size of Sieve Opening in.	Per Cent Passing	Size of Sieve Opening in.	Per cent Passing
2 1/2	100	3/4	38
2	90	1/2	20
1 1/2	78	3/8	12
1	50	No. 4[1]	3
		No. 10	1

1 Standard Tyler Sieve Mesh number



a. View looking downstream from outlet. Note position of pump house in relation to culvert outlet. Natural drainage is to left of pump house. Drainage created by culvert flow is to right of pump house.

b. View looking upstream at culvert outlet. Point of view is from drainage channel created by culvert flow.

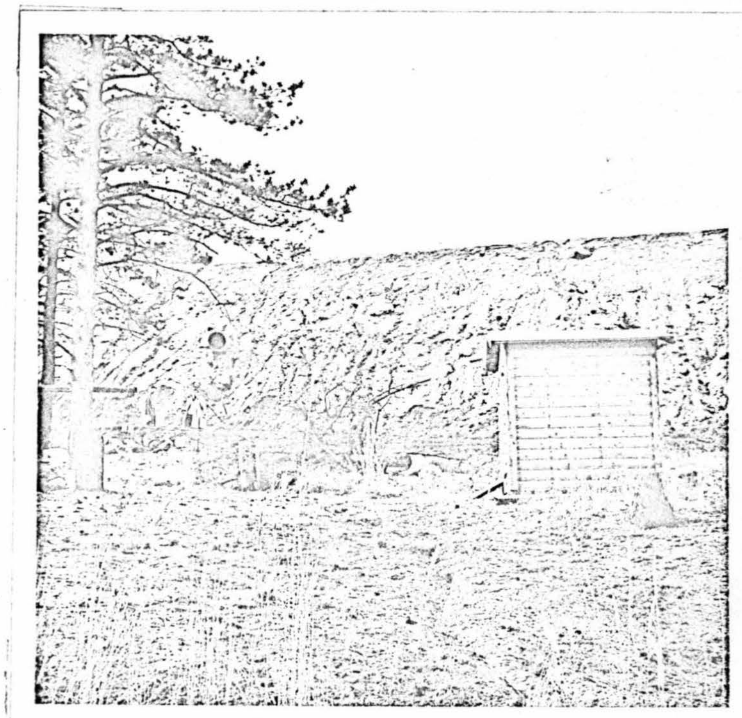
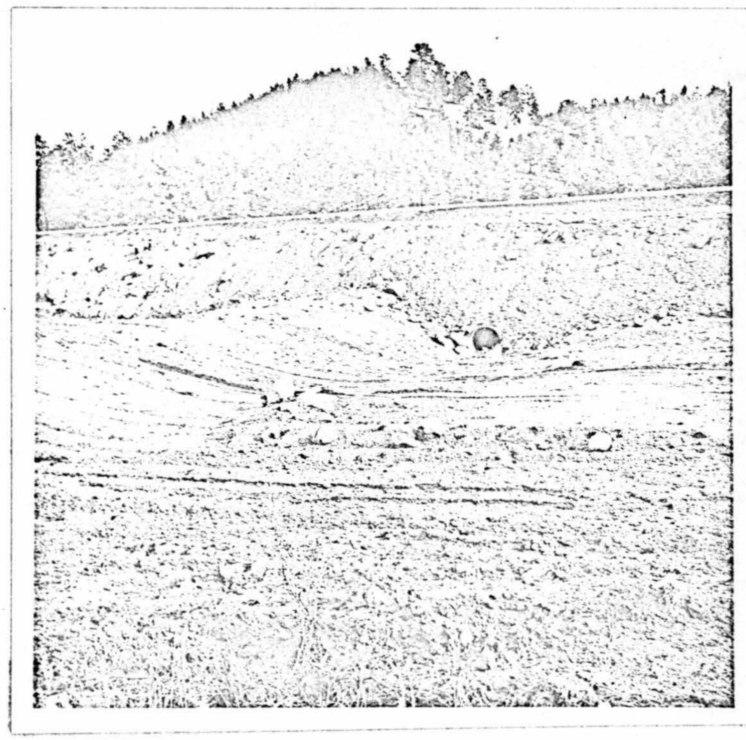


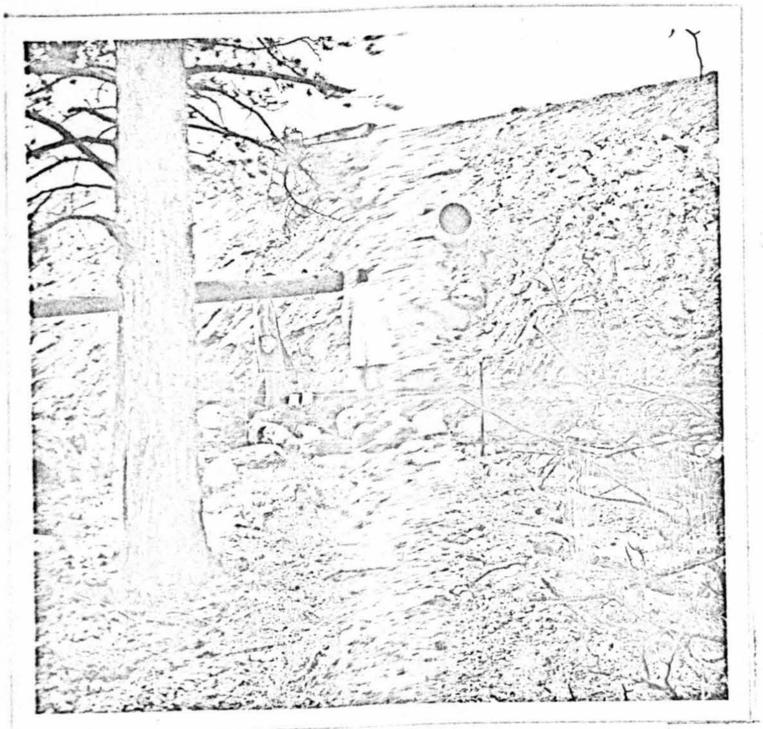
Fig. 1. Location of spring house below c.m. pipe culvert located near Schaffer's Crossing on U.S. Highway 285 in the Turkey Creek watershed.

a. Drainage area--upstream from culvert inlet.



b. Culvert inlet conditions.

Fig. 2. Upstream conditions for inlet to c.m. pipe culvert of Fig. 1.



a. Close-up view of culvert outlet. Large extent of scour below the culvert outlet.

b. Culvert outlet showing location of right-of-way line.

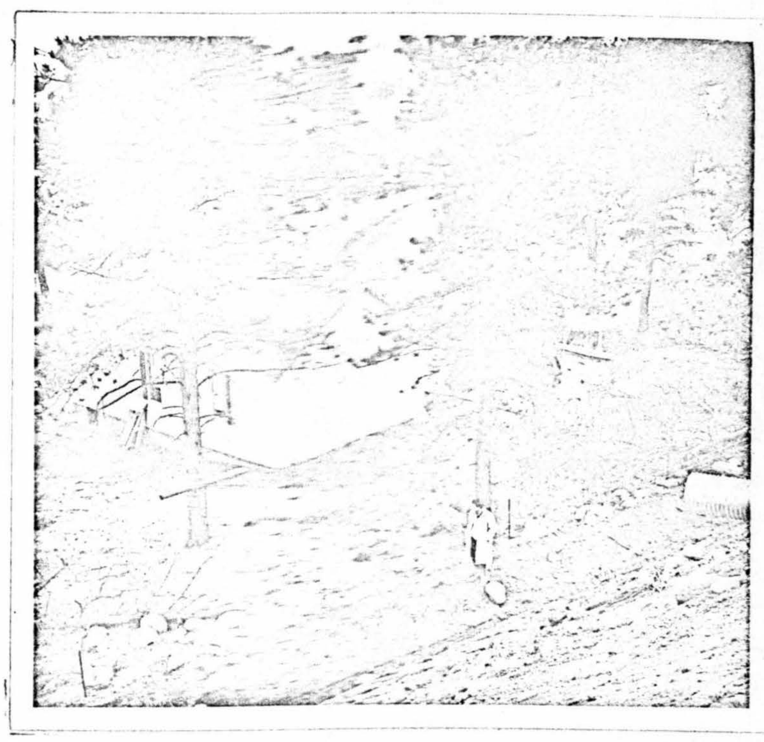


Fig. 3. Close-up view of outlet conditions for c.m. pipe culvert of Fig. 1.

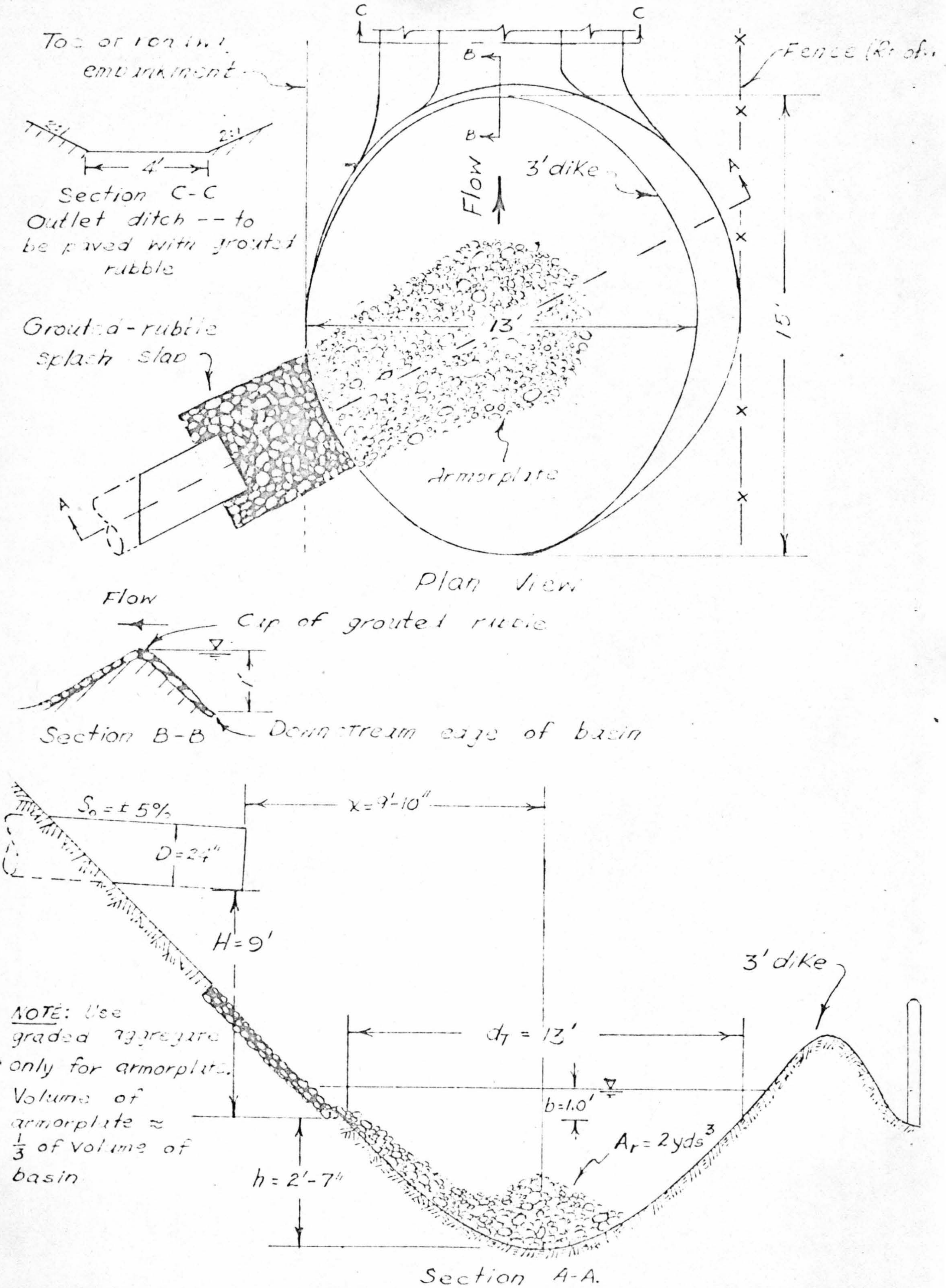


Fig4. Design details for an armorplated stilling basin below a pipe out

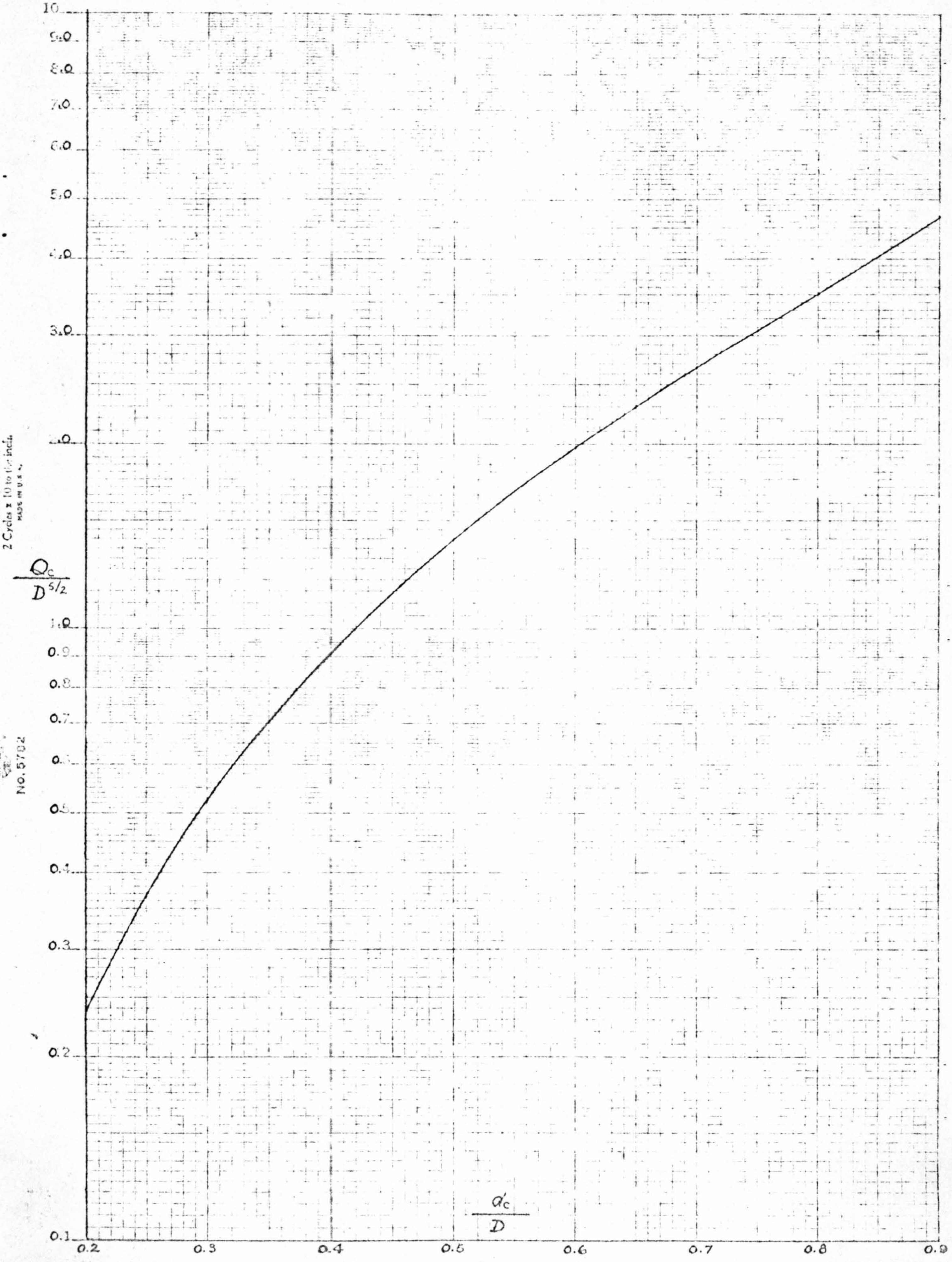


Fig. 5 Partly full flow factors for circular pipes

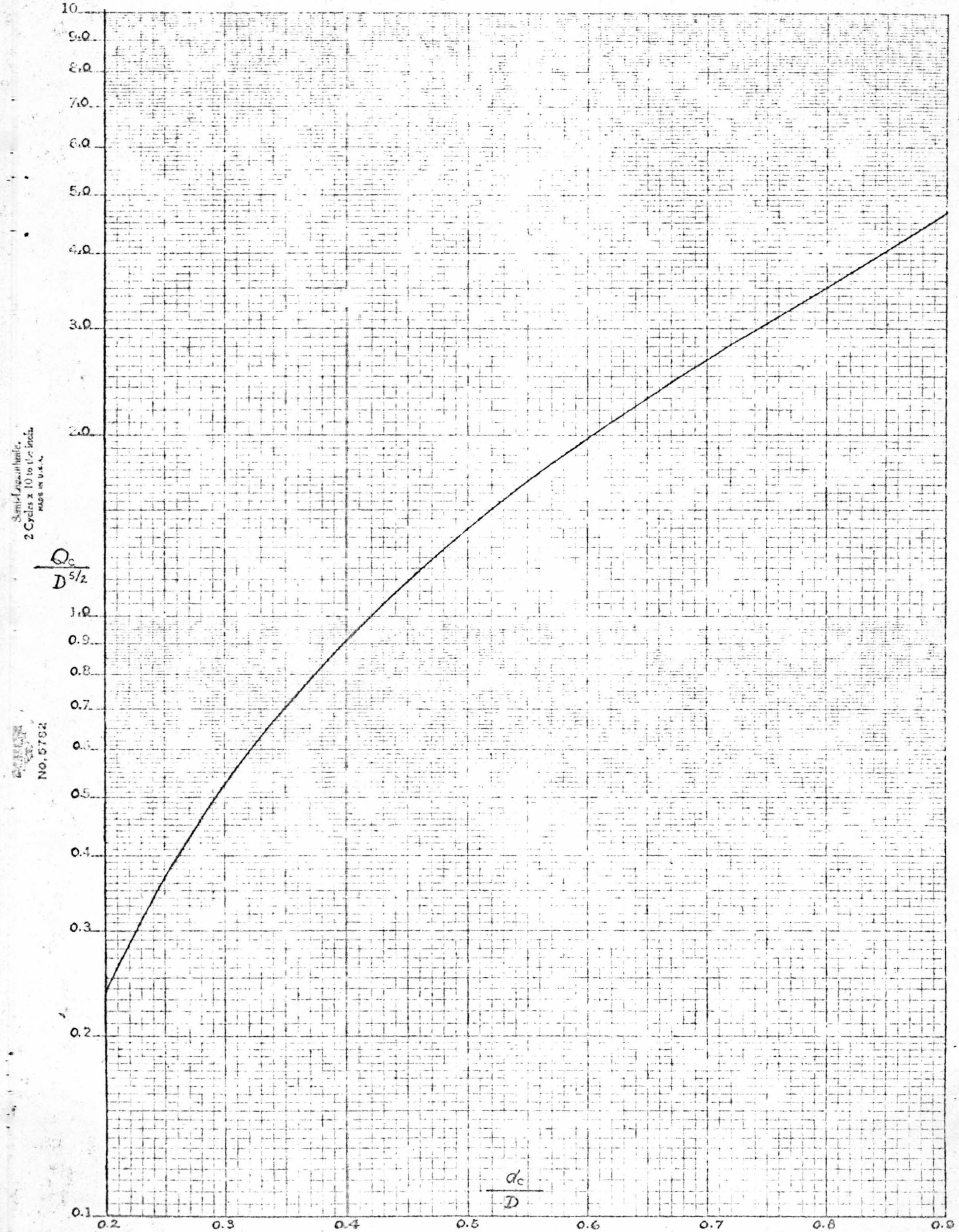


Fig. 5 Partly full flow factors for circular pipes

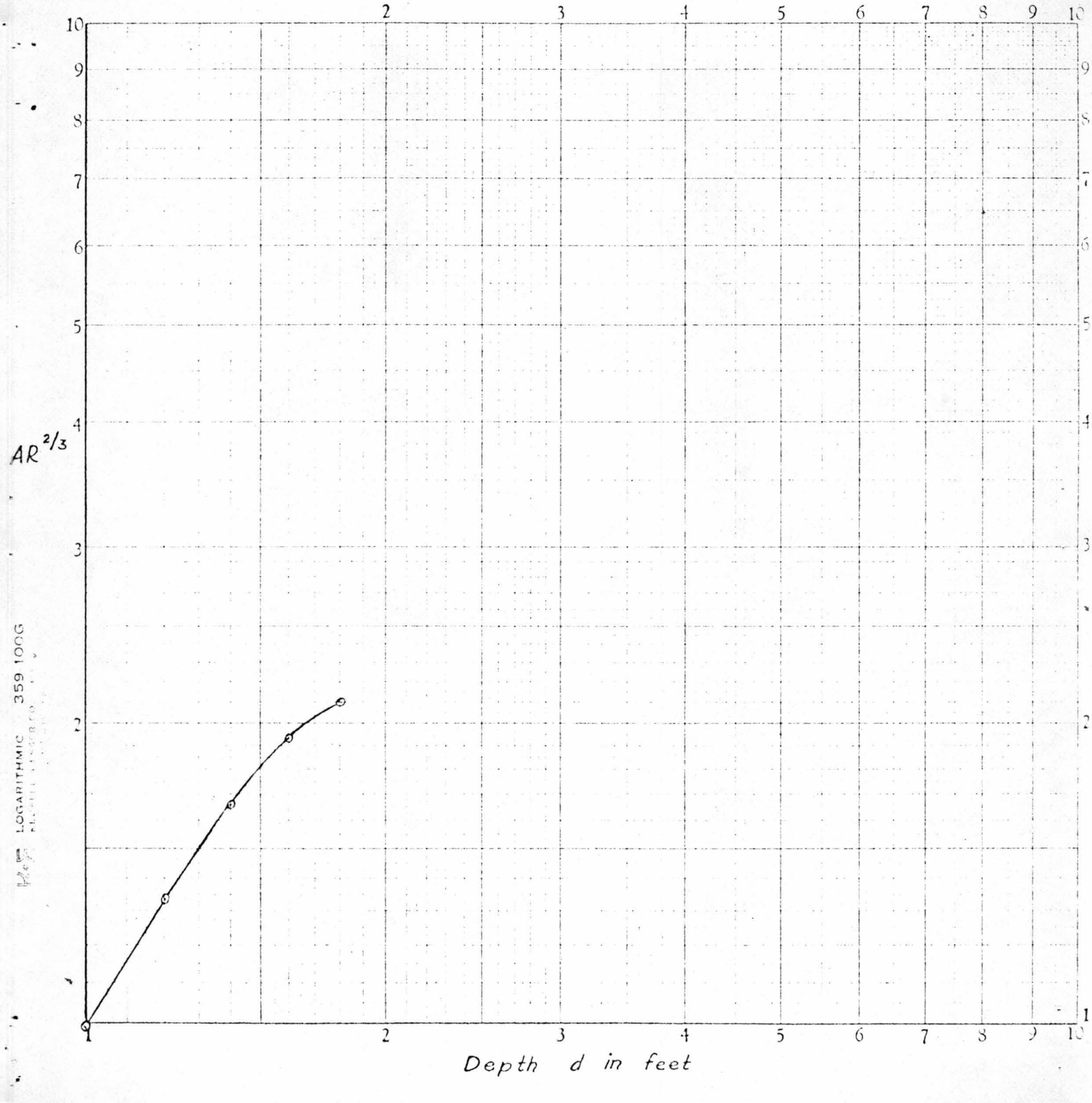


Fig. 6. Graph showing the variation of $AR^{2/3}$ with depth d of flow in a circular pipe of 2 ft diameter.

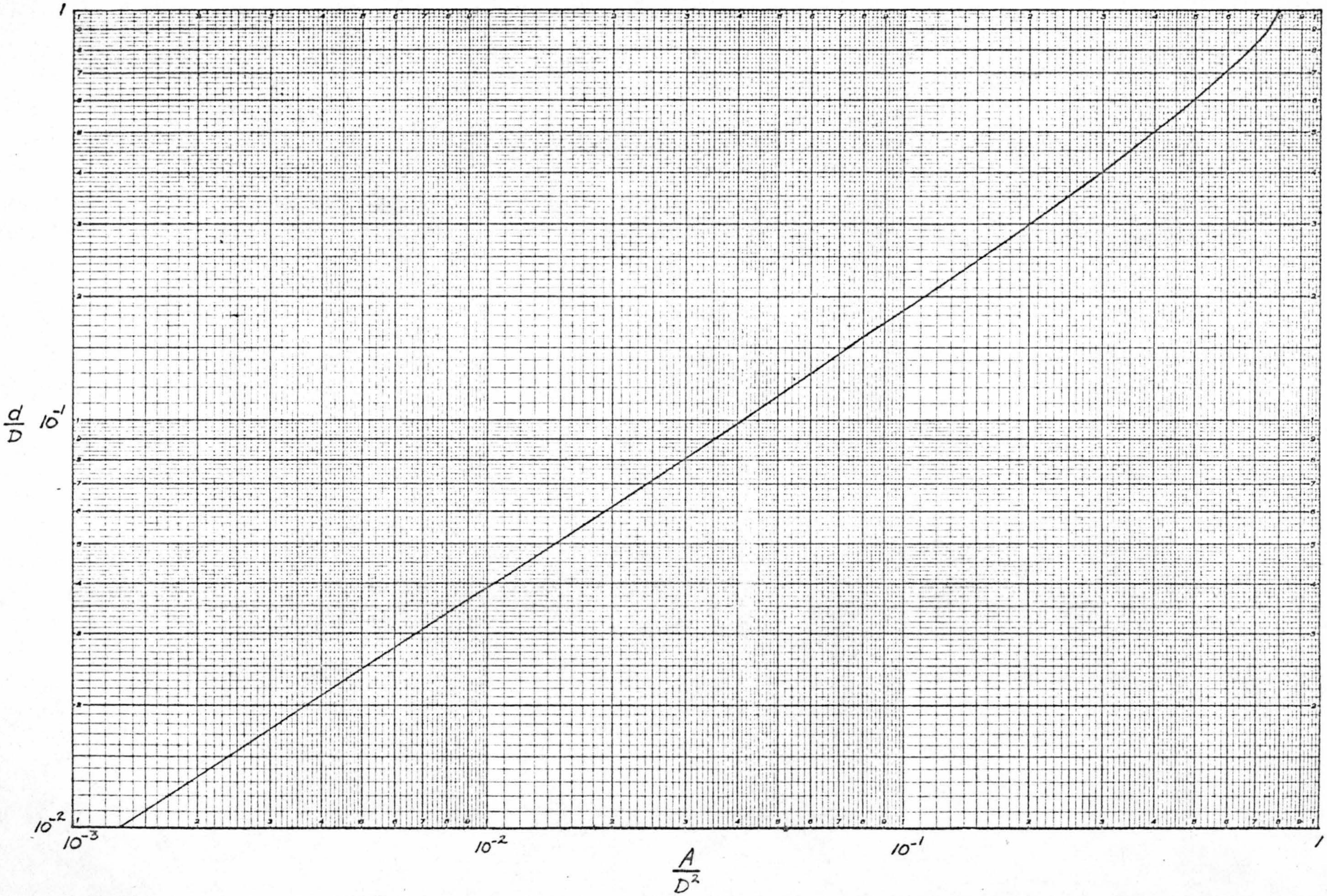


Fig. 7. Hydraulic properties of pipes flowing partly full.

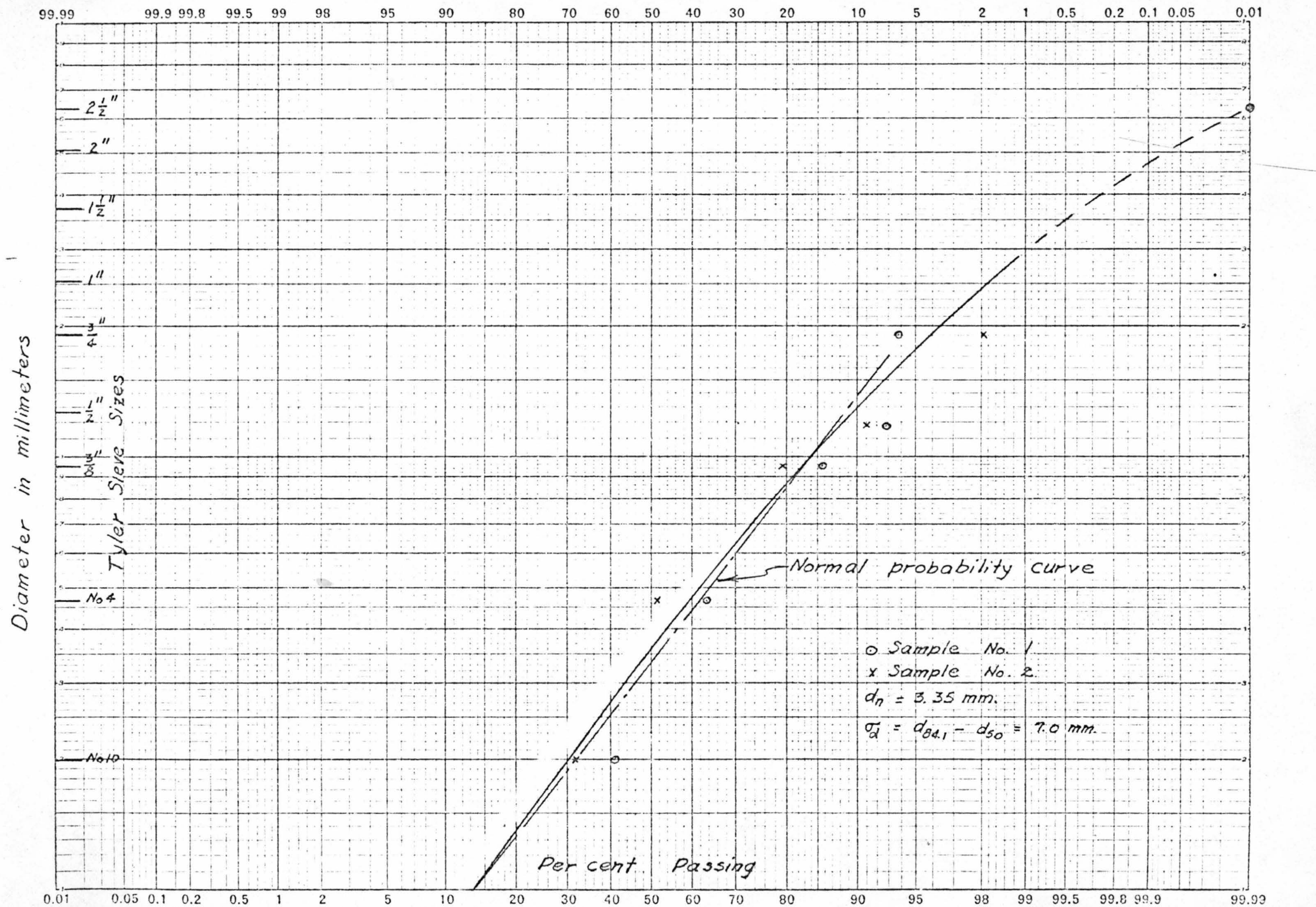
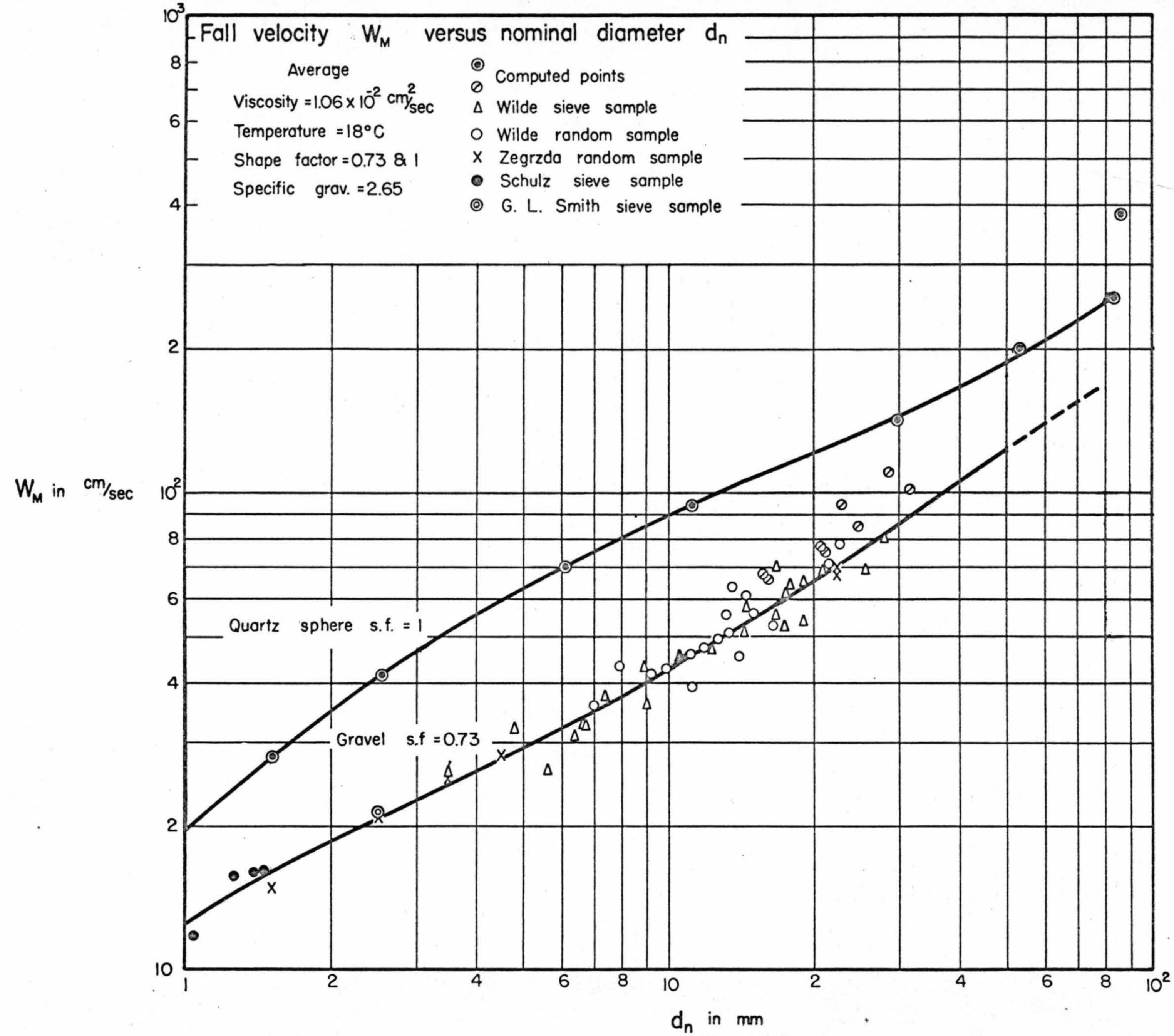
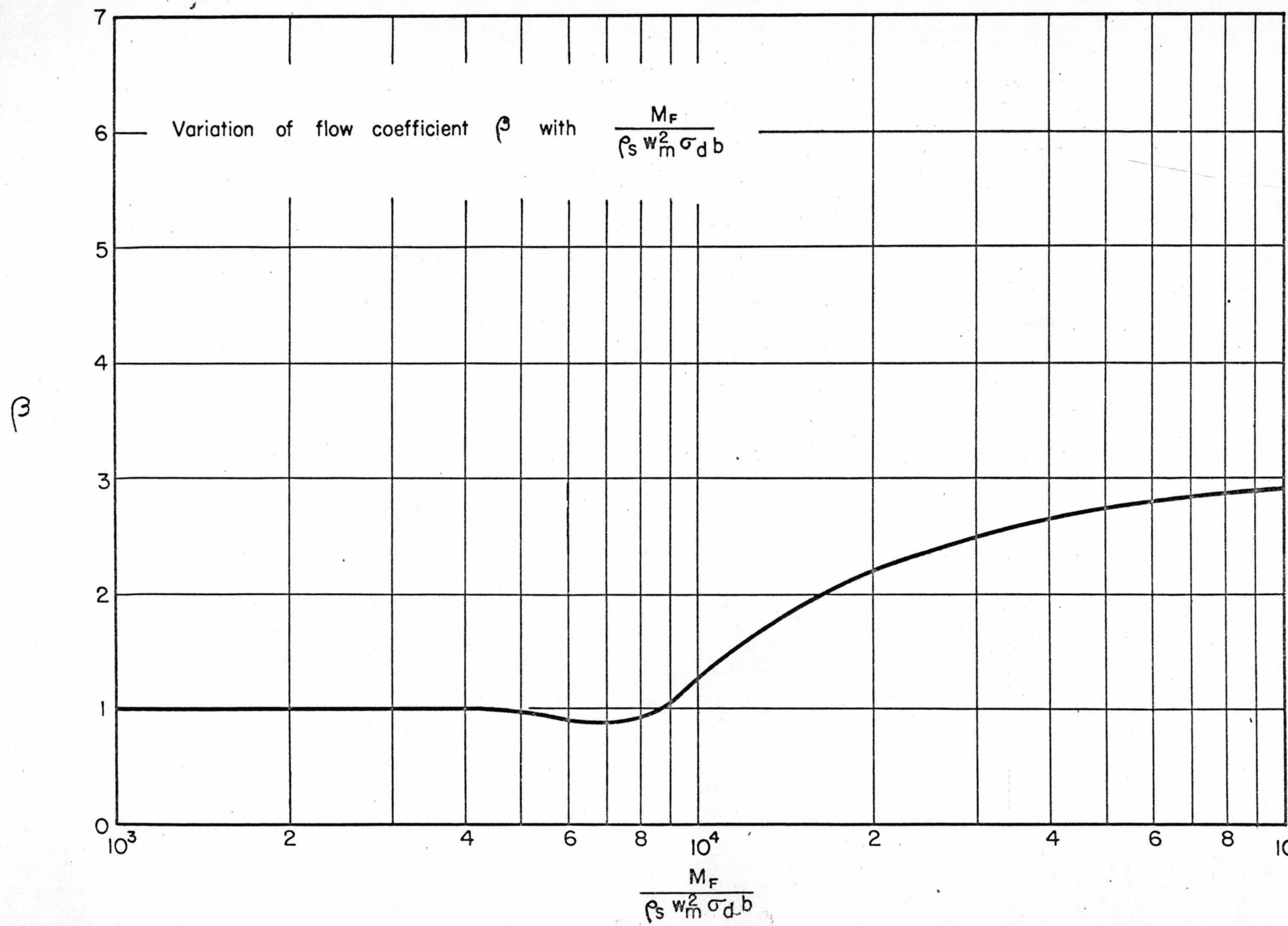


Fig 8. Log-probability plot of the sediment analysis of the subgrade material.



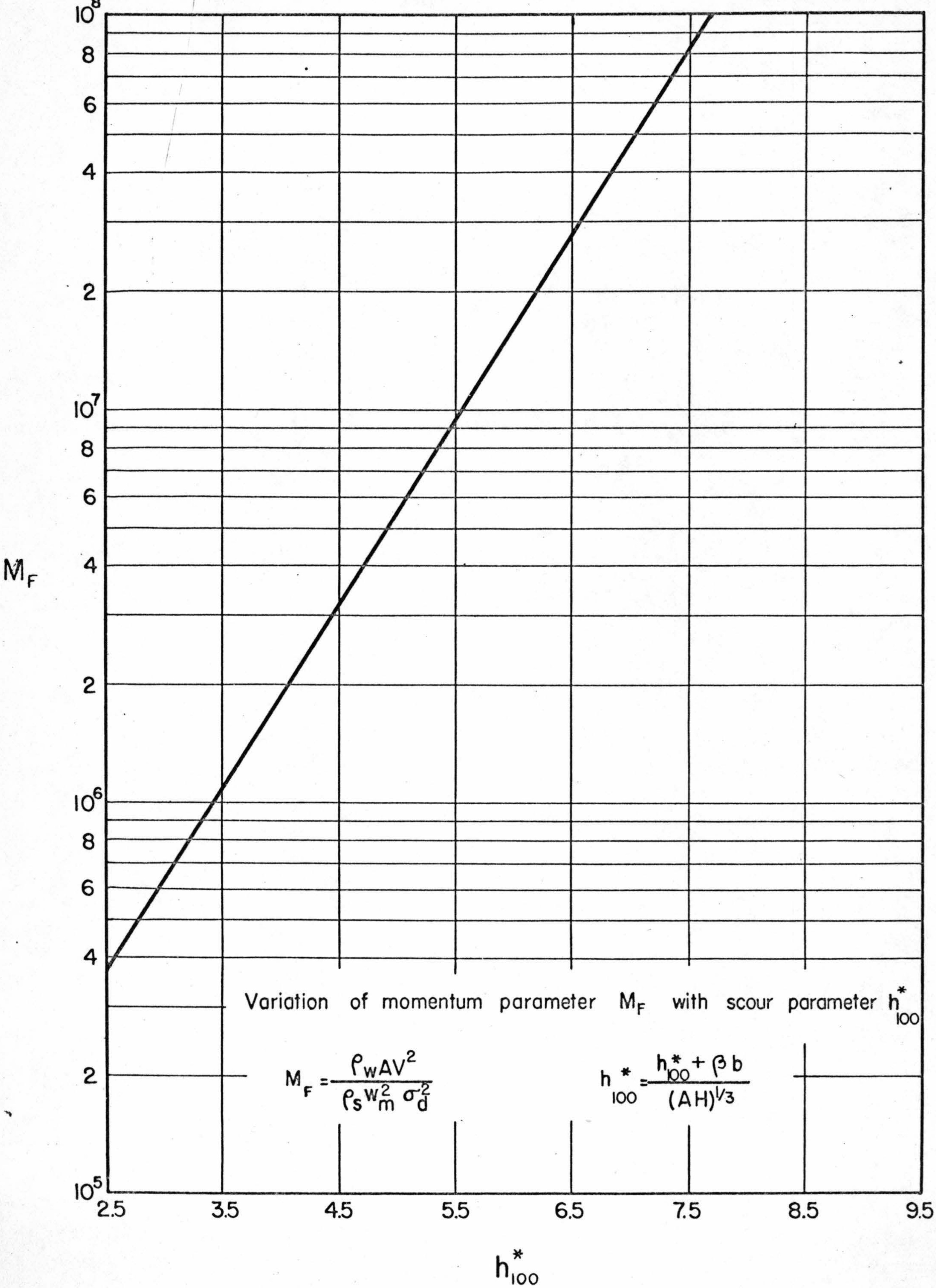
Fall velocity W_M versus nominal diameter d_n
Average
Viscosity = 1.06×10^{-2} cm^2/sec
Temperature = 18°C
Shape factor = 0.73 & 1
Specific grav. = 2.65
Computed points
Wilde sieve sample
Wilde random sample
Zegrzda random sample
Schulz sieve sample
G. L. Smith sieve sample
Quartz sphere s.f. = 1
Gravel s.f = 0.73
W_M in cm/sec
d_n in mm

Fig. 9



Variation of flow coefficient β with $\frac{M_F}{\rho_s w_m^2 \sigma_d b}$
β
7
6
5
4
3
2
1
0
10^3
2
4
6
8
10^4
2
4
6
8
10^5
$\frac{M_F}{\rho_s w_m^2 \sigma_d b}$

Fig. 10



10^8
8
6
4
2
10^7
8
6
4
2
10^6
8
6
4
2
10^5
M_F
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
h^*_{100}
Variation of momentum parameter M_F with scour parameter h^*_{100}
$M_F = \frac{\rho_w A V^2}{\rho_s w_m^2 \sigma_d^2}$
$h^*_{100} = \frac{h^*_{100} + \beta b}{(AH)^{1/3}}$

Fig. 11