Report

On Research Completed Under
J. Waldo Smith Hydraulic Fellowship

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NATURAL ROUGHNESS IN ARTIFICIAL CHANNELS

Submitted
by

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Research Report

NATURAL ROUGHNESS IN AN ARTIFICIAL CHANNEL

Foreword

This study of Natural Roughness in Artificial Channels was originally planned by the hydraulics staff of the Civil Engineering Department at Colorado Agricultural and Mechanical College. The detailed planning, however, together with the design and construction of the flume, and the taking and analysing of the data were done by the research fellow as a part of a master's thesis bearing the same title.

Funds contributed for the project were:

Fellowship - ASCE	$1,000.00
Expenses - ASCE	400.00
Expenses - Colo. A and M College	1,099.00
Total	$2,499.00

Because nearly all of the expense budget was needed for materials, most of the construction of the flume and screens was done by the research fellow. Occasional assistance was given by other graduate students. The designs for the flume and clearing space in the laboratory for the flume began in August of 1950. The flume was completed early in March and preliminary tests and alterations were finished by the first of April. April was spent collecting data and the rough draft of the thesis was completed and questionable data were checked in May. The research was brought to a close on June 4, 1951.

Introduction

Open channels and canals are needed to convey water for many purposes such as water supply, drainage, navigation, flood control, water power, and irrigation. In connection with irrigation, for example, water must be brought from the many storage reservoirs and diversion dams to the land for crop use. The transportation of this water has been a problem of major engineering importance in the past and will continue to be as long as there is water for irrigation.

The objective in any canal design is to carry the required amount of water as efficiently as possible. The canals are often lined with gravel, rock, soil, concrete, or any of a number of the many manufactured linings. This lining is generally used to prevent erosion and possible failure and is one of the determining factors in the resistance offered the flow of water by the canal. The resistance coefficient is the measure of resistance to flow and is generally taken for conditions of steady, uniform flow.

Past Work in This Field

Engineers have developed several formulae for the determination of the discharge of canals and natural streams. These are for the most part based on empirical relations. Of the many proposed, only two have gained general recognition. These two equations are:

(1) the Chezy equation,

$$Q = CA\sqrt{RS} \tag{1}$$

and (2) the Manning equation,

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

Resistance to flow in pipes, which has certain similarities to resistance to flow in open channels, was investigated by Nikuradse who developed a roughness standard by cementing sand grains of definite size to the inside of pipes. Once the standard was established in these pipes artificially roughened with the sand grains, the results from commercially-manufactured pipes could be compared and classified according to the standard.

Purpose of Research

The purpose of the research carried on for the J. Waldo Smith Hydraulic Fellowship was to determine the relationship between artificial roughness and the roughness of natural stream gravels laid loosely in a controllable artificial channel. This relationship is necessary to correlate the work done in the past with artificial roughnesses and the theoretical formulae developed from the results, with the roughness of natural materials such as stream gravels used in canal linings.

Analysis of the Problem

The variables for a dimensional analysis of the subject can be selected from the basic principles of fluid mechanics and hydraulics. The variables affecting the flow in open channels can be classified into three main groups as follows:

The geometry of the channel and the roughness,

d - depth
B - width
λ - shape
k - roughness
S - slope

The flow - - assume steady and unform,

V - velocity

The properties of the fluid,

μ - viscosity
ρ - density
$\Delta\gamma$ - difference in the specific weight of the fluid in the channel and that of the atmosphere above it.

These variables may be expressed in functional form as

$$\phi_1 \,(d,\ B,\ \lambda,\ k,\ S,\ V,\ \mu\ ,\ \rho\ ,\ \Delta\gamma\,) = 0$$

If d, V, and ρ are chosen as the repeating variables and dimensional analysis is employed, the variables can be reduced to six in number:

$$\phi_2 \left(B/d,\ \lambda,\ d/k,\ S,\ dV\rho/\mu\ ,\ V/\sqrt{\frac{\Delta\gamma d}{\rho}}\right) = 0 \qquad (4)$$

where:

B/d = relative width
λ = shape of the channel
d/k = relative roughness or the depth of flow divided by the diameter of the roughness
S = slope
$dV\rho / \mu$ = Re = Reynolds number, the inertia forces relative to the viscous forces
$V/\sqrt{\frac{\Delta\gamma d}{\rho}}$ = Fr = Froude number, the inertia forces relative to the gravitational forces

The Froude number above includes both inertia forces and the force of gravity, and by using it as the dependent variable and assuming that the velocity is proportional to the square root of the slope, Eq. 4 becomes:

$$V = \sqrt{g} \;\; \phi_2 \,(B/d, \; \lambda, \; d/k, \; Re) \; \sqrt{dS} \tag{5}$$

or:

$$V = C_1 \; \sqrt{dS} \tag{6}$$

in which:

$$C_1 = \sqrt{g} \;\; \phi_3 \; (B/d, \; \lambda, \; d/k, \; Re) \tag{7}$$

As it is the aim of the dimensional analysis to combine the variables into dimensionless parameters, Eq. 7 above was divided by $\sqrt{g}$ giving the following:

$$C_2 = D_1 / \sqrt{g} = \phi_3 \; (B/d, \; \lambda \;, \; d/k; \; Re) \tag{8}$$

To simplify the analysis of the results obtained in the experimental work, certain of the variables were held constant. The channel was kept rectangular and the roughness was placed only on the bottom of the channel so that the relative width could be considered infinitely large and the channel shape factor could be considered a constant.

This reduces Eq. 8 to:

$$C_2 = \phi_4 \; (d/k, \; Re) \tag{9}$$

Experimental Equipment and Procedure

The general layout of the equipment used for the experiments is shown in Fig. 1. The equipment consisted of a large tilting flume 43 ft long, with an adjustable side which made it possible to use widths from 4 ft to 8 ft. The depth of the flume was 2 ft measured perpendicular to the bottom of the channel. The water for the experiments was supplied to the system by a 14-in. propeller-type pump and was returned to the sump after passing through the flume. The flow was regulated by a valve at the entrance to the 8-ft by 8-ft head box and partial regulation was also obtained with a bypass valve on the pump outlet. The water entering the flume passed through a needle gate made of tapered vertical slats to give an even distribution of flow across the section and backwater was controlled by another set of needle gates at the exit.

The flume was supported by four sets of telescoping jacks made of pipe. The jacks could be adjusted first in 4-in. increments for rough adjustment and then screws in the top of the jacks were used to make the final fine adjustment. Measurement of the discharge was made using a 10-1/2-in. stainless-steel orifice plate placed in the 14-in. line and connected to a water manometer.

The roughness used in this study consisted of stream gravel screened over a narrow size range. The screens used were hand made of 1/4-in. steel pencil rod welded at the points of contact. Those screens obtained from a local manufacturer proved unsatisfactory because of too wide a variation in the spacing. Although fabricating the screens by hand was a time-consuming and tedious job, this procedure was justified because of the need to use equipment which could be duplicated for research elsewhere. The screen openings measured 7/8, 1-1/8, 1-3/4, 2-1/4, 3-1/2, and 4-1/2 in. clear spacing. The sizes thus obtained were designated 1-, 2-, and 4-in. gravel.

Nearly 10 cu yds of gravel was screened to obtain enough of the three sizes to cover the 43-ft by 4-ft floor of the flume to a thickness thought to be adequate. The gravel was lifted up to the flume by a chain hoist mounted on an overhead 4-in. rail. The rail and loading equipment were designed and built for the job and proved very satisfactory. The 1-in. and 2-in. gravel was placed loosely in the flume and allowed to find its own position, the rocks were placed by hand in the case of the 4-in. gravel as it was too large for the limited supply of water to move. The placing was done so that the rocks were shingled in as natural a manner as possible.

The depth of the water was measured with the aid of hook gages in wells outside the flume and independent of the flume so that they remained stationary when the flume was tilted. The depth was taken as the height of water above the floor of the flume minus a mean thickness of gravel layer.

The flume was designed and constructed from 2-in. by 4-in. lumber and 1/2-in. waterproof (exterior) plywood. It was supported on two 6-in. I-beams set 4-ft apart. These beams, in turn, were held up with 4 sets of jacks as previously described. The jacks were made of pipe welded to old automobile brake drums as bases. Two sets were on hand and served as guides for building the other two sets. The water entered the flume from a permanent 14-in. water line in the laboratory near the head box.

Before actual testing began, the 1-in. gravel (and later the 2-in. gravel) was placed loosely in the flume and allowed to find its most stable position of least resistance to the flow. In many cases the rocks seemed to pile up in somewhat of a pyramid with the rocks on top of the piles locked firmly in place. After the 2-in. gravel had adjusted to its most stable condition, a 6-in. rolling wave of water could pass down the flume without causing movement of the gravel. If the gravel particles were disturbed, normal flow would often move them the entire length of the flume.

When the gravel was first placed in the flume, it was smoothed mechanically as much as possible. Then it was left free to move under the influence of the water so that each particle could seek its own resting place much the same as in nature. When the water was first introduced, considerable movement took place with a very small flow. This movement into pyramids or dunes gave a very rough appearing bottom to the channel. The flow, however, seemed less turbulent after this dune action was completed than when the water first passed over the smoothed gravel. The apparent loss in turbulence after the formation of dunes, points out the possibility that the composite roughness of all the separate particles of gravel is lessened by the mutual interference brought on by the natural placement of the gravel by the water.

The possibility of fastening the particles firmly to the bed of the flume was studied, but because of the unnaturalness and difficulty of duplication it was believed that the procedure described was the most "standard" method. The 4-in. rocks were too large to move with the flow available and were all hand placed in a random shingling effect such as was observed in the case of the 1-in. and 2-in. material. Figs. 8 to 15 show the rocks as they were found during and after testing.

Before any experiments were run with a particular size gravel after it was placed in the flume and leveled, the gravel was brought to a state of equilibrium as described. When testing was ready to begin, the channel was set to the desired slope and then checked with a surveyors level.

The pump was started and the flow was regulated with both the valve at the head box and the by-pass valve at the pump. When the minimum flow that could be read on the water manometer was reached, testing began.

Each experiment was called a run and each group of runs for a certain slope was called a set. All sets with a certain size gravel were called a series. The 2-in. gravel constituted series I with the 1-in. making up series II and the 4-in. series III. For each series of runs the slopes were changed in 0.5 percent increments to make 5 sets and the discharges were varied to give about 5 runs per set. Because almost no trouble from backwater was encountered at very low depths, the initial run for each set of experiments was made at a low discharge.

Backwater was corrected by adjusting the needle gates to obtain both M_1 and M_2 curves so that the true normal depth could be determined more accurately. The hook gages in the stilling wells were set each time and the extent and nature of the backwater curve was observed. At very low depths, the M_2 curve was insignificant because the backwater was restricted to the extreme ends of the flume. As the discharge was selected for each new run, hook gages and the needle gates were adjusted so that normal depth occurred -- the surface of the water was parallel to the bed. For final determination of the mean depth, only gages at distances of 15 to 30 feet from the entrance were used. When in place, the gage 10-ft from the entrance seemed to be in the zone of unestablished flow. When the flow became established, the turbulence originating from the bed had worked its way upward to cause an irregular surface where the eddies appeared and spread horizontally. The gage 40-ft from the head box was in the zone of effect from the exit conditions and therefore was only used to measure the backwater curve in determining the mean depth. After the mean depth was established, the discharge manometer was read. Then the hook gages were read after which the discharge manometer was read the second time. The discharge was computed for an average of the manometer readings.

When a series was completed with one size gravel, that gravel was removed and the next size was placed in the flume and brought to a stable condition. After the gravel showed no further signs of movement, testing began as in the previous series.

About one quarter of the flume length was needed to establish steady flow and a short length was used at the lower end of the flume in correcting for backwater. A longer flume would have been much more desirable. Furthermore, because the turbulence condition changed along a large part of the 43-ft length of the flume (as evidenced with the 1-in. gravel) and because of backwater effects, a flume of considerable length would be essential to obtain accurate data for flat slopes or small gravel sizes.

Interpretation of Results

In the dimensional analysis approach to the problem, it was decided that the data taken could best be presented by plotting the resistance coefficient C g as some function of the relative roughness d k and Reynolds number Re. After some study, however, such a plot seemed unnecessary because the conditions were always turbulent and the variation with Reynolds number was insignificant. Instead, Manning's n vs the relative roughness d/k was plotted for the convenience of those who prefer to work with Manning's equation.

The results of the study are plotted on Figs. 16 and 17 and both show some of the same tendencies. The relative roughness d/k is the depth of the water divided by the diameter of the gravel used. The value of Chezy's C was computed from the formula $C = \dfrac{Q}{A \quad \sqrt{dS}}$.

The use of d instead of the hydraulic radius is justified as there was no roughness placed on the sides and the channel could be considered infinitely wide. Manning's n was computed from the equation $n = \frac{1.486}{V} d^{2/3} S^{1/2}$.

The fact has been proved in the past that the values of Chezy's C and Manning's n are not constant for all types of flow in a particular channel in a particular state of repair. Fig. 16 and 17 were plotted to establish the variation of these coefficients of roughness with the change in the relative roughness. In Fig. 16, the plot of Chezy's resistance coefficient against the relative roughness, there seems to be a smooth curve for the three sizes of gravel at the greatest slope which was 2.5 percent. The points for the smaller slopes drifted somewhat from this curve possibly because of the limitations of the equipment. In Fig. 17, the plot of Manning's n vs d/k the relative roughness, the curve shows an increase in roughness with depth up to about d/k equal to 2 or 3. The curve then has a gradual reversal of the slope until the normal decrease in n for an increase in depth becomes manifest for larger values of d/k.

The curves change slope at a value of relative roughness of about 2. El Samni (3) (University of California, Berkeley) found in his work on pressures exerted on bed material that for a relative roughness of over 2, channel roughness could be expected but below that value it changed to channel irregularity. The plots in Fig. 16 and 17 seem to imply that this phenomenon applies to natural roughness in an artificial channel as well. Although a relative roughness of 2 is not practical for irrigation canals, this study does show that the characteristics for channels do change for very low depths of flow. This change to channel irregulatiry at low values of relative roughness should be investigated further.

Suggestions for Further Study

The data presented in this report show a definite need for more research with a larger water supply and a longer flume. Although the data were taken over a narrow range, due to the limitations of the equipment, the trends shown in the plots of the data indicate that considerable information could be obtained with a longer flume and a larger water supply. The use of gravel screened over a narrow size range merits further study as the present plots show some tendency for grouping by sizes. A wider range of relative roughness values will be needed to establish a relationship between natural and artificial roughnesses.

Acknowledgements

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Figure

Fig. 8 4-in. gravel after testing was completed

Fig. 13 2-in. gravel with top half of the rocks showing at point taken as datum

Fig. 14 1-in. gravel after completion of tests

Fig. 15 Movement of bed near entrance of flume which occurred at a slope of 2-1/2 %

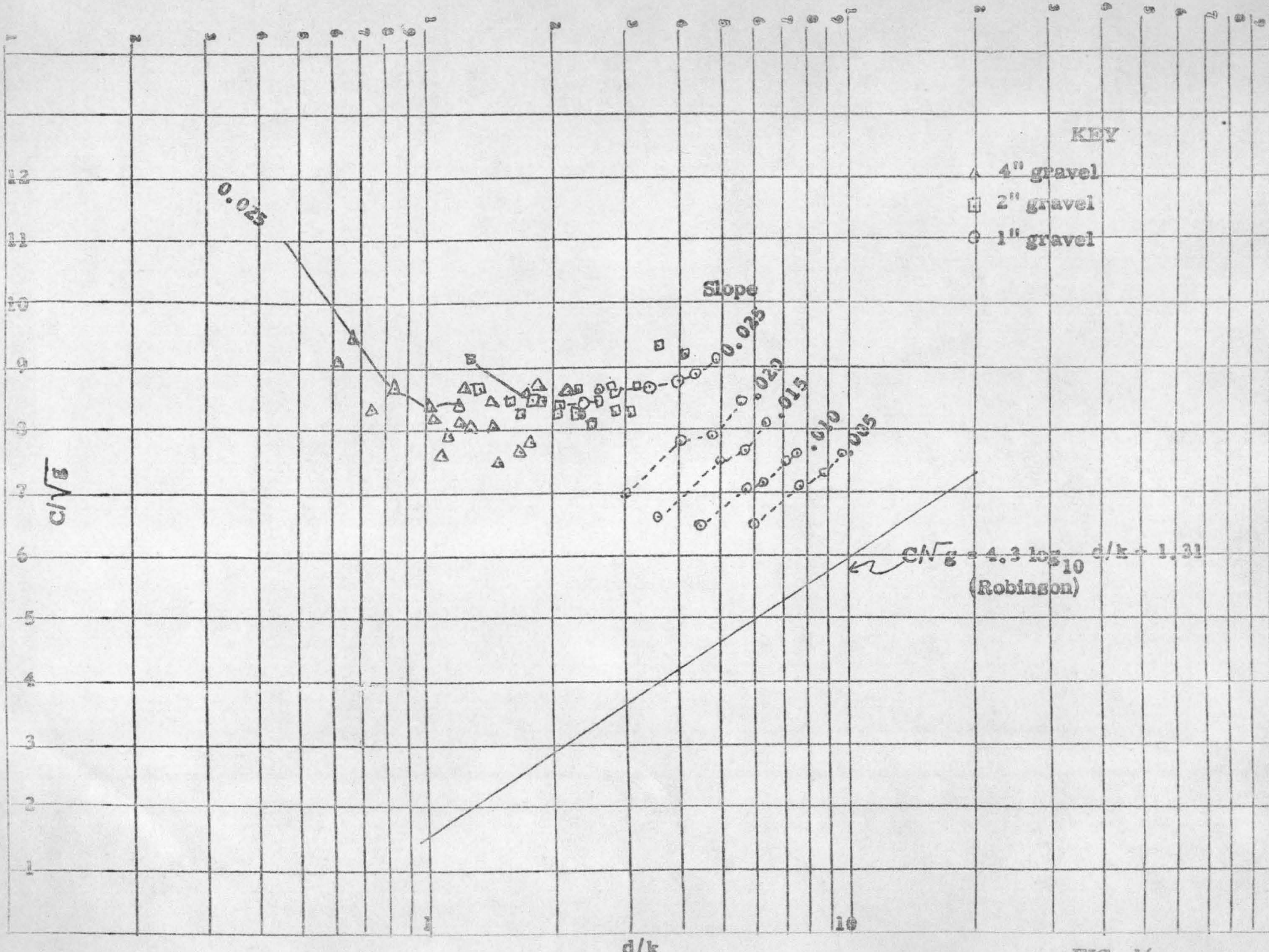
KEY
4" gravel
2" gravel
1" gravel
Slope
0.025
0.025
0.020
.015
.010
.005
$C/\sqrt{g} = 4.3 \log_{10} d/k + 1.31$
(Robinson)
$C/\sqrt{g}$
d/k
1
10
12
11
10
9
8
7
6
5
4
3
2
1

FIG. 16

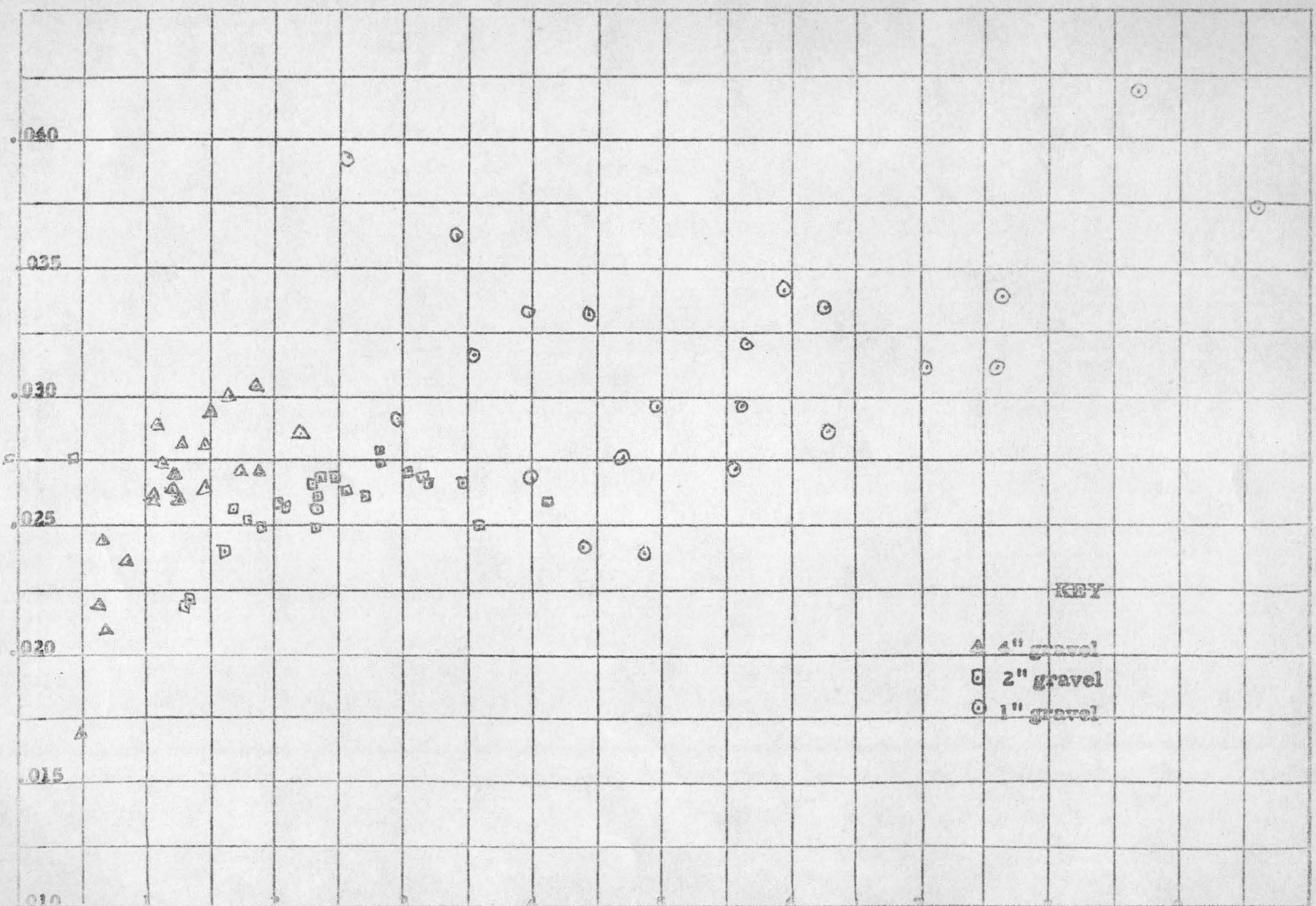

FIG. 17

Table 1. - - EXPERIMENTAL DATA FOR TWO-INCH GRAVEL (series I).

Run	Slope	Disch cfs	d ft	Vel ft per sec	$C/\sqrt{g}$	n	d/k
1	0.005	3.32	0.385	2.16	8.68	0.02485	2.30
2	"	3.48	.390	2.23	8.90	0.02415	2.33
3	"	5.39	.528	2.55	8.73	0.02662	3.16
4	"	6.15	.576	2.66	8.72	0.02672	3.45
5	"	8.42	.684	3.08	9.26	0.02585	4.10
6	"	8.50	.681	3.12	9.38	0.02505	4.08
7	"	6.92	.594	2.91	9.40	0.02499	3.56
8	0.010	2.92	.290	2.52	8.34	0.02571	1.67
9	"	4.66	.384	3.03	8.60	0.02572	2.30
10.	"	6.14	.457	3.36	8.73	0.02603	2.74
11.	"	7.51	.524	3.58	8.73	0.02680	3.14
12	0.015	3.31	.268	3.09	8.56	0.02400	1.60
13	"	5.70	.392	3.68	8.30	0.02690	2.35
14	"	5.95	.410	3.63	8.14	0.02690	2.46
15	"	7.47	.468	3.99	8.36	0.02740	2.80
16	"	8.35	.504	4.14	8.37	0.02711	3.02
17	"	4.57	.339	3.37	8.33	0.02585	2.03
18	0.020	8.50	.468	4.54	8.68	0.02787	2.80
19	"	6.27	.379	4.14	8.37	0.02597	2.27
20	"	4.84	.314	3.85	8.52	0.02495	1.88
21	"	2.94	.221	3.32	8.76	0.02303	1.32
22	0.025	8.54	.425	5.02	8.58	0.02632	2.54
23	"	7.36	.388	4.74	8.47	0.02606	2.32
24	"	6.15	.345	4.46	8.44	0.02579	2.06
25	"	4.99	.298	4.19	8.57	0.02507	1.78
26	"	3.25	.213	3.81	9.20	0.02188	1.28

Table 2.--EXPERIMENTAL DATA FOR ONE-INCH GRAVEL (series II).

Run	Slope	Disch cfs	d ft.	Vel ft per sec	$C/\sqrt{g}$	n	d/k
1	0.005	3.68	0.496	1.85	6.54	0.03422	5.94
2	"	5.85	.636	2.30	7.17	0.03388	7.62
3	"	7.27	.724	2.51	7.35	0.04186	8.67
4	"	8.83	.802	2.75	7.65	0.03731	9.60
5	0.010	3.37	.370	2.27	6.56	0.03354	4.43
6	"	6.16	.522	2.95	7.20	0.03330	6.25
7	"	7.76	.588	3.30	7.54	0.03113	7.04
8	"	8.78	.634	3.46	7.63	0.03108	7.59
9	"	5.24	.471	2.78	7.09	0.03218	5.64
10	0.015	2.95	.294	2.51	6.66	0.03165	3.52
11	"	5.57	.413	3.37	7.53	0.02968	4.95
12	"	6.97	.470	3.71	7.77	0.02959	5.62
13	"	8.61	.529	4.11	8.18	0.02862	6.28
14	0.020	2.74	.245	2.80	7.04	0.02922	2.93
15	"	6.24	.390	4.00	7.96	0.02753	4.67
16	"	8.65	.464	4.66	8.50	0.02719	5.55
17	"	4.89	.333	3.67	7.88	0.02679	3.98
18	0.025	8.57	.406	5.28	9.20	0.02386	4.86
19	"	7.18	.367	4.89	8.97	0.02409	4.39
20	"	6.05	.330	4.50	8.86	0.03328	3.95
21	"	4.75	.283	4.20	8.79	0.03624	3.39
22	"	3.05	.212	3.60	8.70	0.03933	2.54

Table 3.--EXPERIMENTAL DATA FOR FOUR-INCH GRAVEL (series III).

Run	Slope	Disch cfs	d ft.	Vel ft per sec	$C/\sqrt{g}$	n	d/k
1	0.005	3.74	0.412	2.27	8.78	0.02604	1.24
2	"	6.02	.574	2.62	8.62	0.02711	1.72
3	"	6.84	.618	2.77	8.78	0.02745	1.86
4	"	8.65	.726	2.98	8.67	0.02862	2.18
5	0.010	3.31	.362	2.63	7.69	0.02892	1.09
6	"	6.05	.497	3.04	7.57	0.02941	1.49
7	"	7.25	.555	3.27	7.74	0.03000	1.67
8	"	8.80	.623	3.53	7.87	0.03043	1.87
9	0.015	2.38	.206	2.89	9.14	0.02183	0.62
10	"	4.71	.345	3.41	8.22	0.02615	1.04
11	"	5.81	.401	3.62	8.18	0.02697	1.20
12	"	7.96	.480	4.14	8.57	0.02642	1.44
13	0.020	3.32	.248	3.35	8.40	0.02443	0.74
14	"	5.85	.372	3.93	7.99	0.02742	1.12
15	"	7.07	.421	4.20	8.04	0.02816	1.26
16	"	8.65	.478	4.52	8.12	0.02804	1.44
17	0.025	2.45	.155	3.95	11.18	0.01676	0.46
18	"	4.61	.278	4.14	8.74	0.02366	0.84
19	"	6.04	.341	4.43	8.42	0.02594	1.02
20	"	7.67	.400	4.79	8.43	0.02632	1.20
21	"	3.65	.224	4.07	9.56	0.02095	0.67