Paper No. 5079.

"The Effect of the Form of Cross-Section on the Capacity and Cost of Trunk Sewers." †

By Thomas Donkin, Assoc. M. Inst. C.E.

Correspondence.

Mr. E. H. Essex pointed out that the Author, in his opening statement on p. 261 § that "When considering the design of a trunk sewer, the usual practice is to use either a circular or an egg-shaped form of cross-section", overlooked the fact that engineers formerly made use of other cross-sections. Instances were to be found in the records of Kutter's Abstract Science ‡, and the statement could certainly not be said to hold good since May 1936, when Mr. J. L. Davies had designed a U-shaped trunk sewer 1½ mile long *; he had submitted the design to the Ministry of Health for their approval, and he succeeded, after frequent references to the book of Tables and diagrams referred to by the Author on p. 266 §, in persuading the Ministry somewhat tardily to agree to the granting of the necessary permission to raise a loan for what their official advisers thought fit to inform him was an entirely new departure in sewer-construction. The work had since been completed at Leatherhead by Mr. Davies, the design showing many advantages both during construction and in after use. There seemed to be great misconception of the very decided advantages of that U-shaped design for trunk sewers; for although a semicircular channel gave as good a cross section as any for the bottom half of a sewer, and the diameter of the channel could be made to suit the available gradient to give a self-cleansing gravity flow for the minimum discharge, the full circular sewer was the worst possible cross section for efficiency of discharge, and were it not for its constructional advantages, the circular section would, in all probability, have long since been abandoned.

On p. 262 § the Author stated that "When calculating the size of any particular type of sewer, a gradient is first of all assumed, from which the size is obtained." Surely that was as novel a procedure as the suggestion

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† Journal Inst. C.E., vol. 7 (1937–38), p. 261 (December 1937.)

§ Page numbers so marked refer to the Paper. (Footnote (†) above.)—Sec. Inst. C.E.

‡ W. R. Kutter, "Versuch zur Aufstellung einer neuen allgemeinen Formel für die gleichförmige Bewegung des Wassers in Canälen und Flüssen." Second edition, 1877. *Translated into English by* R. Hering and J. C. Trautwine *and published in 1899.*

* "Sewerage and Sewage Disposal in a Newly Constituted Urban Area." Journal Inst. M. & Cy. E., vol. lxiii (1936–37), p. 110.

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to design the sewer to suit one particular formula? In nearly every instance the engineer found his gradient decided for him beforehand by the natural contour of the drainage-area. At Leatherhead it was desired to raise the discharge-level at the sewage-disposal works by at least 18 inches, in order to give better distribution over the filter-beds, and a gradient of 1 in 1,000 was all that was available. Any circular sewer should have a self-cleansing velocity of 1½ foot per second at the proportionate depth of 0·2, which represented 12 times the minimum dry-weather flow when full, and thus the ratio $V/\sqrt{S}$ had to equal the value of $C\sqrt{R}$. To have taken a value of $C=124\sqrt[6]{R}$ would have meant that the sewer would have needed to be designed to a size larger than that adopted by Mr. Davies.

On p. 275 § the Author stated, very erroneously in Mr. Essex's opinion, that "it is the crown-gradient and not the invert-gradient which decides the capacity of the sewer and provides the datum from which a basis of comparison can be made"; on p. 266 § he also made a statement which could not be supported by facts: "it is obvious that, for the same diameters, the capacity of the U-shaped section is 13·80 per cent. greater than the capacity of the circular section." Mr. Essex had prepared a Table (part of which was shown as Table XVI, pp. 412–413 §) and *Fig. 7* (p. 414 §) to show the discharge of Mr. Davies's U-shaped culvert as compared with the discharge of a 24-inch circular sewer of equal area; it would be seen that the maximum discharge of the U-shaped sewer was 10 cusecs, compared with 8·15 cusecs for circular section (or 12·25 per cent. more), when not quite full, and 8 cusecs, compared with 7·74 cusecs (showing an advantage of 10·3 per cent.) when flowing full, that was to say, under pressure.

The Author further stated on p. 269 § that the dry-weather flow in most trunk sewers forming part of a combined system represented something in the neighbourhood of 1 per cent. of the total discharge, and, whilst not accepting the accuracy of that statement, Mr. Essex would like to point out that it emphasized the advantage of the U-shaped cross section, which could be regulated to give a self-cleansing velocity for the dry-weather flow and provided ample top accommodation for storm-flows before relief overflows came into action. The late Sir Joseph Bazalgette, Past-President Inst. C.E., had said that "trunk sewers should never be called upon to discharge under pressure flow," and that statement was a strong argument in favour of the U-shaped cross section; with that section the sewer could not become surcharged so long as the outlet was free, whereas the upper half of the circular sewer was always more or less under pressure-flow, with the result that at every inspection-manhole the flow spread itself over the benchings and the outlet became surcharged. With the U-shaped section, however, the flow passed through the inspec-

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§ *Ibid.*

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TABLE

Depth: feet.	Depth/diameter.	Area: square feet.	Perimeter: feet.	Hydraulic mean depth: foot.	Velocity, V: feet per second.
24-inch circular section: S=0·00077; fall=1					
0·1	0·05	0·058	0·902	0·065	0·62
0·2	0·1	0·164	1·286	0·127	1·00
0·4	0·2	0·447	1·854	0·242	1·53
0·5	0·25	0·614	2·094	0·293	1·73
0·6	0·3	0·793	2·32	0·342	1·92
0·8	0·4	1·173	2·73	0·429	2·21
0·836	0·418	1·241	2·80	0·442	2·29
1·0	0·5	1·571	3·142	0·500	2·46
1·2	0·6	1·971	3·55	0·555	2·62
1·4	0·7	2·349	3·97	0·592	2·72
1·6	0·8	2·694	4·43	0·608	2·77
1·8	0·9	2·978	4·99	0·596	2·74
2·0	1·0	3·142	6·28	0·500	2·46
25½-inch × 21-inch U-shaped section: S=0·00092;					
0·087	0·05	0·045	0·790	0·057	0·62
0·175	0·1	0·1245	1·127	0·1112	1·00
0·35	0·2	0·342	1·622	0·211	1·53
0·525	0·3	0·606	2·03	0·299	1·92
0·700	0·4	0·899	2·398	0·376	2·21
0·823	0·47	1·105	2·64	0·418	2·39
0·875	0·5	1·202	2·745	0·4375	2·46
1·0	—	1·423	3·00	0·474	2·62
1·2	—	1·782	3·40	0·524	2·80
1·4	—	2·149	3·80	0·566	2·92
1·6	—	2·524	4·20	0·602	3·02
1·8	—	2·907	4·60	0·632	3·13
1·92	—	3·1416	4·84	0·650	3·18
1·92	—	3·1416	6·84	0·460	2·55
2·0	—	3·298	5·00	0·659	3·22
2·125	—	3·546	5·25	0·675	3·27
2·125	—	3·546	7·25	0·490	2·64
3·125*	—	5·55	7·25	0·766	3·55

* After sewer-depth increased by 12 inches.

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XVI.

Discharge, Q: cusecs.	VR.	$\log \frac{VR}{\nu}$	Chezy's C.	$V/\sqrt{R}$	$\frac{P}{R}$.

in 1,300 (if $C=124\sqrt[6]{R}$, gradient is 1 in 1,000).

			$A = 25$	$E = 0{\cdot}698$	
0·035	0·041	3·52	88	2·44	13·81
0·164	0·127	4·02	100·5	2·81	10·11
0·684	0·370	4·48	112	3·11	7·69
1·06	0·507	4·61	115·2	3·20	7·15
1·52	0·656	4·72	118	3·28	6·77
2·60	0·947	4·89	122	3·38	6·37
2·80	1·00	4·91	122·7	3·40	6·35
3·87	1·23	5·00	125	3·47	6·28
5·16	1·45	5·06	126·5	3·52	6·40
6·39	1·61	5·11	127·7	3·54	6·70
7·41	1·68	5·13	128·2	3·56	7·27
8·15	1·63	5·12	128	3·55	9·43
7·74	1·23	5·00	125	3·47	12·57

fall 1 in 1,090 (if $C=124\sqrt[6]{R}$, gradient is 1 in 850).

			$A = 25$	$E = 0{\cdot}758$	
0·0278	0·0353	3·46	86·5	2·60	13·81
0·1245	0·1112	3·96	99·0	3·00	10·11
0·524	0·323	4·42	110·5	3·33	7·69
1·162	0·573	4·67	116·7	3·51	6·77
1·985	0·828	4·83	120·7	3·60	6·37
2·64	1·00	4·91	122·7	3·71	6·30
2·96	1·075	4·94	123·5	3·72	6·28
3·73	1·24	5·00	125	3·80	6·34
5·00	1·47	5·08	127	3·87	6·50
6·27	1·65	5·13	128·2	3·88	6·70
7·63	1·82	5·17	129·2	3·92	7·00
9·11	1·98	5·20	130	3·94	7·30
10·0	2·07	5·22	130·5	3·96	7·44
8·00	1·17	4·98	124·5	3·76	14·90
10·6	2·12	5·23	130·9	3·96	7·60
11·6	2·22	5·25	131·2	3·98	7·78
9·35	1·29	5·02	125·5	3·77	14·80
19·70	2·72	5·34	133·5	4·06	—

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tion-manholes without change of shape, and even bends forming change of direction in the flow could be designed so as to cause very little reduction in the discharge.

Mr. Essex thought that engineers had been led astray by mathematicians who could have little knowledge and no practical experience on the

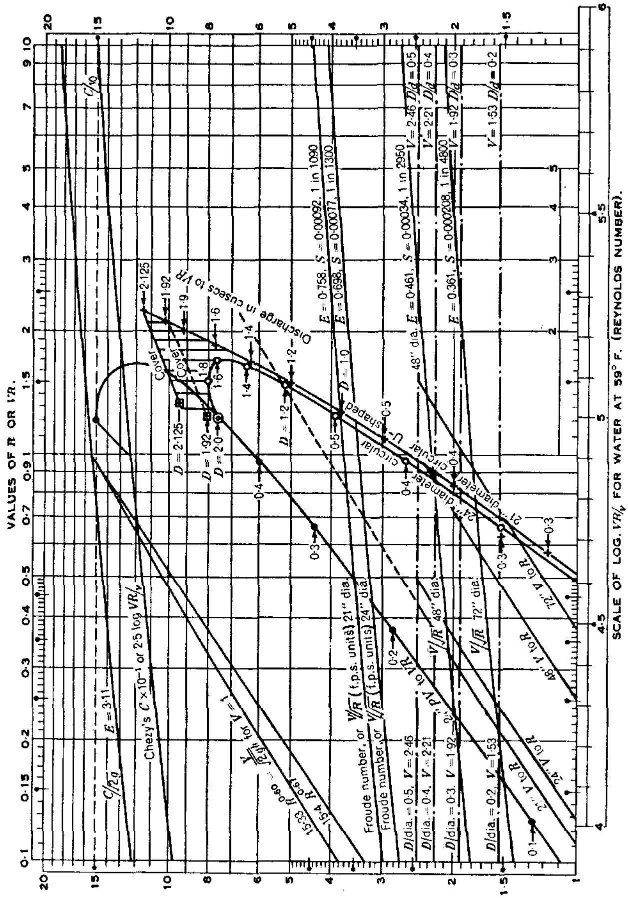

Fig. 7.

subject; the problem of unaccelerated sewage-flow might be usefully examined on a small scale in the laboratory for pipes under pressure, and the National Physical Laboratory had rendered valuable service in enabling it to be shown that for pipes under pressure the Chezy coefficient C was a function of the Reynolds number, and, following the law of organic growth, might be written $C=A$ Log (Reynolds number). For gravitational flow in pipes not under pressure the correct solution would only be satisfactorily settled by rational argument amongst practical designers

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after close and careful study of the abstract science of the subject. Consideration of the Chezy coefficient could never be abandoned, nor must the close relationship of that coefficient to the Reynolds number or to the Froude number be lost sight of. Mr. F. C. Scobey, on p. 18 of Bulletin No. 150 *, gave it as his considered opinion that " The variation of Kutter's *n* values for identical surfaces renders Kutter's formula unreliable when considered with a constant value of *n* " ; what practical reliance could, therefore, be placed upon the formula used by the Author in the compilation of his Tables, when the inventor of the formula stated that it was based on Kutter's formula and gave a value of *n* between 0·012 and 0·013, while at the same time it could be seen that it gave a value of Chezy's C of $124\sqrt[6]{R}$? Mr. Essex had shown elsewhere ‡ how very unreliable Kutter's formula could be, and how limited was the application of any logarithmic formula of the type $h=\frac{fV^n}{R^y}$, especially where the sum of the indices $n+y$ was other than 3 and so could not comply with the law of similarity of flow laid down by Osborne Reynolds in 1883.

On p. 80 of Bulletin No. 150 *, Mr. F. C. Scobey had tabulated a list of the sum of those indices from different formulas dating from 1775 to 1927. The formula of Beigeleisen in 1914, where $n=1{\cdot}80$ and $y=1{\cdot}20$, and that of Williams and Hazen, where $n=1{\cdot}852$ and $y=1{\cdot}167$, most closely complied with the Chezy formula taking $C=A \log VR/\nu$. On p. 262 § the Author stated that " The accepted method of calculating the velocity and the discharge of any sewer or open channel, no matter what its form of cross-section may be, is by means of an expression of the following form :— $V=CM^xI^y$," and the formula he used was $h=0{\cdot}000065\,\frac{V^2}{R^{1\cdot333}}$ in which the sum of the indices was 3·333. That formula could not comply with the law of similarity of flow, and the Author's Tables would consequently prove to be misleading. In the following two pages he attempted to show in terms of radius what mathematicians had unquestionably led engineers erroneously to believe : namely, that area and discharge varied as the square of the diameter of the pipe, and that perimeter and hydraulic mean depth varied directly as the diameter. Although that might be sufficiently accurate to enable a tentative design of cross section to be obtained, some adjustment was needed. A little rational thought would explain that, for if the perimeter, when the pipe was half-full, were measured at the sides, the proportionate depth of flow in the centre would be bound to be something less than half the diameter, so that if the ratio P/R were to be retained at the usually accepted figure of 6·28 a

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* "Flow of Water in Riveted Steel and Analogous Pipes." Washington, 1930.

‡ " Abstract Science and Academic Theory in Relation to Hydraulic Flow in Concrete Pipes and Culverts." Journal Inst. M. & Cy.E., vol. lviii (1931–32), p. 1863.

§ *Ibid.*

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slightly larger area than half of the total area of the circular cross section would be needed. The commonly accepted theory that the same velocity existed in a pipe flowing half-full as in one flowing full appeared to be disapproved by the data published on p. 18 of Bulletin No. 854 of the U.S.A. Department of Agriculture *; practical engineers, however, realizing that Chezy's C was a function of VR/ν knew that the discharge in cusecs was PVR, and that $Q/P=VR$ was a ratio which could be more accurately measured in the field than in the laboratory. Setting aside academic considerations, the following points were established:

(1) The discharge of the U-shaped section, calculated by any formula, exceeded that of the circular section by 12 per cent. when not quite full, and by 10 per cent. when full and under pressure.

(2) The U-shaped section never needed to become surcharged.

(3) The velocities set out in Table XVI showed a self-cleansing velocity of 1½ foot per second in the circular pipe for one-twelfth of the full capacity of 6 times the maximum dry-weather flow; at the latter discharge the circular sewer was full and under pressure, and anything above 6 times the maximum dry-weather flow was bound to find a storm relief on the town side of the sewage-disposal works. The Leatherhead culvert had been given a preference of 1½ inch in height over the 2-foot circular pipe, requiring only an addition of ½ cubic foot of concrete per yard run of culvert; the discharge had, however, been increased by a further 16 per cent., or by a total of 42 per cent. in excess of the maximum discharge of the 24-inch circular-section sewer.

(4) The question of future enlargement of a trunk sewer became less vital; an allowance being made for keeping all branch-connexions at only 1 foot above the top of the trunk sewer meant that by raising the slab only 12 inches at any future date the Leatherhead sewer could be increased in area to 5·55 square feet, the perimeter to 7·25 feet, and the hydraulic mean depth to 0·766 foot; the velocity would then be 3·55 feet per second, and the discharge would then be 19·70 cusecs, an increase of 70 per cent. for comparatively little extra expenditure and no trouble in dealing with the flow of sewage.

(5) The construction of U-shaped culverts permitted easy inspection during construction, and any defective workmanship became at once apparent.

(6) The initial saving in cost, compared with the circular section, would be at the least 10 per cent.

Mr. C. B. Lea, of Pretoria, thought that the chart reproduced as Fig. 8 (facing p. 418) might be found useful for determining the velocity in the

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* D. L. Yarnell and S. M. Woodward, "The Flow of Water in Drain Tile." 1925.

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sewer sections mentioned, when used in conjunction with the Tables at the end of the Paper. The chart was based on Manning's formula $v=\frac{1\cdot486}{n}R^{\frac{2}{3}}S^{\frac{1}{2}}$, which was the same as Santo Crimp's and Bruges's formula, when n had a value of 0·012. The chart was plotted on logarithmic paper and the lines running from the top left-hand corner to the bottom right-hand corner represented some value of nv. That product was divided by n by the lines running approximately at right angles, and hence the value of v could be determined. The ordinates represented the hydraulic mean depth in feet and the velocity in feet per second, both to the same scale. The abscissae represented the slope of the conduit. The following examples should make the use of the chart clear :—

EXAMPLE 1. To determine the velocity in a conduit, the hydraulic mean depth (R) being 2·0, the slope being 0·01, and the coefficient of roughness (n) being 0·015.

First, the point of intersection of $R=2\cdot0$ and $S=0\cdot01$ should be found. From that point it was necessary to travel upwards parallel to the nv lines (shown dotted) until the line for $n=0\cdot015$ was reached, and then to travel horizontally to the velocity scale, which gave the required velocity as 16 feet per second.

EXAMPLE 2. To find the velocity in a sewer when $R=1\cdot0$, $S=1/1000$, and $n=0\cdot012$.

From the point of intersection of $R=1\cdot0$ and $S=0\cdot001$, it was necessary to travel upwards parallel to the nv lines. The left-hand margin was, however, met before the line for $n=0\cdot012$, so that from the point of intersection with the margin (at 3·3 approximately) it was necessary to travel horizontally to the right-hand margin and then to continue upwards parallel to the nv lines until the required value of n was reached. In the example chosen the value of n was read on the broken lines in the right-hand bottom corner, and the velocity was about 3·8 feet per second.

The chart had been originally prepared for designing storm-water channels, and was used in conjunction with a Table giving the values of A and R for various channels. In the case of an earth channel the maximum velocity was fixed, and knowing the discharge required, A was fixed. Then knowing the values of S and n the maximum value of R was found by working backwards on the chart. With A and R known it was then a simple matter to select a suitable channel. Similarly, from Table XVII (p. 418), the size of a pipe could be obtained for assumed conditions.[1]

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[1] The values in Table XVII were obtained by slide-rule. A check of the figures by machine showed that, in general, the error was less than 1 per cent., but in a few cases it was nearly 2 per cent. The Table was intended for use with Fig. 8, and for that purpose the accuracy was ample.—C.B.L.

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TABLE XVII.

Pipe-diameter : inches.	Depth of flow as a proportion of the pipe-diameter.									
	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0
	Area: square feet.									
	0·040d^2	0·112d^2	0·198d^2	0·293d^2	0·393d^2	0·492d^2	0·587d^2	0·673d^2	0·745d^2	0·785d^2
	R: foot									
	0·063d	0·121d	0·171d	0·214d	0·250d	0·277d	0·296d	0·304d	0·297d	0·250d
4	0·0044 0·0208	0·0122 0·0403	0·0216 0·0570	0·0319 0·0713	0·0428 0·0833	0·0545 0·0924	0·0639 0·0987	0·0733 0·1012	0·0812 0·0990	0·0855 0·0833
6	0·0100 0·0312	0·0280 0·0605	0·0495 0·0855	0·0732 0·1070	0·0982 0·1250	0·1230 0·1385	0·1466 0·1480	0·1682 0·1520	0·1863 0·1485	0·1962 0·1250
8	0·0178 0·0417	0·0498 0·0807	0·0882 0·1140	0·1304 0·1426	0·1749 0·1665	0·2190 0·1845	0·2610 0·1972	0·2990 0·2025	0·3320 0·1980	0·3490 0·1665
9	0·0225 0·0468	0·0630 0·0908	0·1114 0·1282	0·1650 0·1605	0·2210 0·1875	0·2770 0·2075	0·3300 0·2220	0·3790 0·2280	0·4190 0·2230	0·4420 0·1875
10	0·0278 0·0521	0·0777 0·1008	0·1375 0·1424	0·2035 0·1783	0·2725 0·2080	0·3410 0·2310	0·4070 0·2465	0·4670 0·2530	·05170 0·2473	0·5450 0·2080
12	0·040 0·063	0·112 0·121	0·198 0·171	0·293 0·214	0·393 0·250	0·492 0·277	0·587 0·296	0·673 0·304	0·745 0·297	0·785 0·250
15	0·063 0·078	0·175 0·151	0·310 0·214	0·458 0·267	0·615 0·313	0·770 0·346	0·918 0·370	1·051 0·380	1·164 0·372	1·228 0·313
18	0·090 0·094	0·252 0·182	0·446 0·256	0·659 0·321	0·885 0·375	1·105 0·416	1·320 0·443	1·515 0·456	1·675 0·446	1·766 0·375
21	0·123 0·109	0·343 0·212	0·607 0·299	0·899 0·375	1·203 0·438	1·507 0·485	1·800 0·518	2·060 0·532	2·282 0·520	2·406 0·438
24	0·160 0·125	0·448 0·242	0·792 0·342	1·170 0·428	1·570 0·500	1·970 0·554	2·350 0·592	2·693 0·608	2·980 0·594	3·142 0·500
27	0·202 0·141	0·567 0·272	1·000 0·384	1·480 0·482	1·990 0·565	2·490 0·623	2·970 0·666	3·410 0·684	3·770 0·669	3·970 0·565
30	0·25 0·156	0·70 0·303	1·24 0·428	1·83 0·535	2·46 0·625	3·07 0·693	3·67 0·740	4·21 0·760	4·66 0·743	4·91 0·625
36	0·36 0·188	1·00 0·363	1·78 0·513	2·64 0·642	3·54 0·750	4·43 0·832	5·28 0·888	6·05 0·912	6·70 0·892	7·07 0·750
42	0·49 0·219	1·37 0·423	2·43 0·598	3·59 0·749	4·82 0·875	6·03 0·970	7·20 1·036	8·25 1·063	9·14 1·039	9·63 0·875
48	0·64 0·250	1·79 0·484	3·17 0·684	4·69 0·856	6·29 1·000	7·87 1·107	9·40 1·184	10·77 1·217	11·92 1·188	12·56 1·000
54	0·81 0·281	2·27 0·545	4·02 0·770	5·93 0·964	7·95 1·125	9·95 1·246	11·89 1·332	13·63 1·368	15·09 1·336	15·90 1·125
60	1·00 0·313	2·80 0·605	4·95 0·855	7·33 1·070	9·83 1·250	12·30 1·384	14·68 1·480	16·82 1·520	18·63 1·485	19·61 1·250
66	1·21 0·344	3·39 0·666	5·99 0·941	8·87 1·178	11·89 1·375	14·88 1·523	17·75 1·628	20·35 1·672	22·55 1·634	23·75 1·375
72	1·44 0·375	4·03 0·727	7·13 1·025	10·55 1·284	14·15 1·500	17·72 1·661	21·13 1·776	24·22 1·824	26·82 1·782	28·25 1·500

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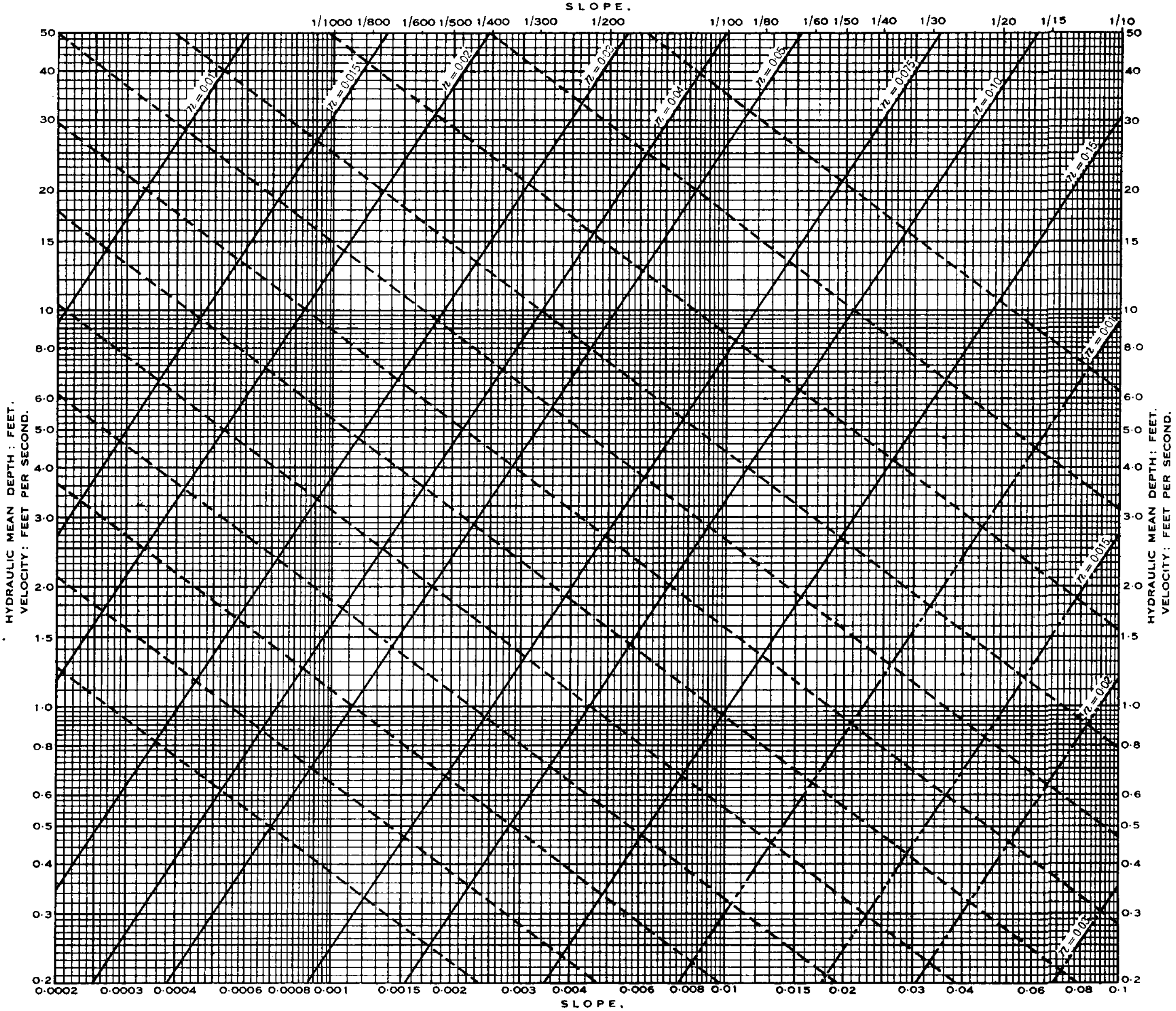
FIG: 8.



UNIVERSAL FLOW-VELOCITY CHART.

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The Author, in reply, observed that Mr. Essex referred to a U-shaped sewer constructed at Leatherhead by Mr. J. L. Davies in May, 1936, and that he pointed out that the work, which had since been completed, showed many advantages both during construction and in after use. The design as submitted by Mr. Davies was apparently regarded by the Ministry of Health as an entirely new departure in sewer-construction. Since that particular aspect of the case had been raised by Mr. Essex, the Author submitted the following statement to make the point entirely clear.

A scheme for the reconstruction and diversion of the Catherine Street and Wellington Lane sewer, Sunderland, designed by the Author and including 950 linear yards of from 36-inch by 36-inch to 48-inch by 48-inch U-shaped sewer, had been submitted to the Ministry of Health in February, 1933, the Ministry signifying their approval in March of that year. The work had been put out to tender in May 1933, and had been completed in June 1934, at a total cost, including subsidiary sewers, of approximately £27,000.

The U-shaped sewer constructed by Mr. Davies at Leatherhead was of form No. 1 (see p. 265 §), with tapering sides, measuring 25½ inches in height by 21 inches in width. In the Author's opinion, although the Leatherhead sewer offered certain advantages with regard to self-cleansing velocities, the dimensions were too small to offer any economic advantages.

Reference to *Figs. 6* (p. 277 §) showing the comparative costs of circular and U-shaped sewers, would, no doubt, make that quite clear.

Mr. Essex agreed that U-shaped sewers had very decided advantages over other forms, and he stated that there appeared to be a great misconception with regard to those advantages. The Author, however, was unaware of any general consensus of opinion with regard to U-shaped sewer design, and he hoped that the publication of his Paper would draw attention to its undoubted advantages.

Mr. Essex suggested that the selection or assumption of a gradient in order to determine the size of a sewer was a novel procedure, and whilst in certain instances the engineer might find his gradient already determined for him, the Author had very vivid recollections of laying down a series of trial gradients and of making comparative estimates from them, to determine the most economical method of dealing with the particular problem in hand. Surely Mr. Essex did not suggest that in each and every instance a sewer-gradient was so irrevocably determined that he could not exercise his skill in determining that combination of gradient and size which would result in his sewer being constructed in the most economical manner ?

Mr. Essex suggested that for a circular sewer a self-cleansing velocity of 1½ foot per second should be obtained at the proportionate depth of 0·2, but the Author was unable to understand why that particular depth should represent twelve times the minimum dry-weather flow when the

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§ *Ibid.*

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sewer was running to full capacity. The Author presumed that the self-cleansing velocity of 1½ foot per second at a proportionate depth of flow of 0·2 applied to the average dry-weather flow for a sewer designed to carry twelve times the average dry-weather flow when full, as part of a foul-sewer system.

Using Mr. Essex's figures in Table XVI (pp. 412, 413) for a 24-inch circular section, 0·4 foot of depth represented a proportionate depth of 0·2, with a velocity of 1·53 foot per second, and a discharge of 0·684 cusec, which approximated to one-twelfth of the discharge when flowing full, that was to say 7·74 cusecs.

It was further stated that if the self-cleansing velocity were to be 1½ foot per second at a proportionate depth of flow of 0·20, then since $V/S^{\frac{1}{2}} = CR^{\frac{1}{2}}$, it was possible to determine the necessary diameter of sewer to fulfil those particular conditions.

It was quite true to say that to take a value of $C = 124R^{\frac{1}{6}}$ rather than the value $C = 25 \log \frac{VR}{\nu}$ would result in a larger sewer-diameter, but that showed the effect of employing different formulas and bore no relationship to the form of cross-section.

With regard to the comment made on the statement relative to crown-gradients, the Author wished to point out that the crown of the sewer should properly represent the hydraulic gradient for which it was designed, whatever the form of cross-section might be, and for that reason he had used the crown as the basis for comparing costs.

Table XVI (pp. 412, 413) had been used to compare the relative discharges of circular and U-shaped sewers. An examination of the Table, however, revealed that the calculated discharges for the 24-inch circular sewer were for a gradient of 1 in 1,300, whilst those for the 21-inch U-shaped sewer were for a gradient of 1 in 1,090. In addition to that, the discharges quoted by Mr. Essex in his remarks were for sewers of equal area. The Author, however, in making his comparison, had quite clearly indicated that he compared sewers of equal diameter and equal gradients, whereas Mr. Essex had compared sewers of equal areas, unequal diameters and unequal gradients. It was quite evident, therefore, that any inference drawn from Table XVI could not be used as a criticism of the figures given by the Author in Tables I and III (pp. 280–281 §).

The Author had prepared Tables XVIII and XIX which showed the properties of 24-inch diameter circular and U-shaped sewers at gradients of 1 in 1,300, in accordance with the formula used by Mr. Essex to determine the value of Chezy's C.

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§ *Ibid.*

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TABLE XVIII.—CIRCULAR SEWERS.

Diameter : 24 inches.
Area : 3·142 square feet.
Velocity : 2·45 feet per second.
Slope : 1 in 1,300.
Hydraulic mean depth : 0·50 foot.
Discharge : 7·70 cusecs.

Depth : feet.	Area : square feet.	Perimeter : feet.	Hydraulic mean depth : foot.	Velocity, V : feet per second.	Discharge : cusecs.	VR.	Log $\frac{VR}{\nu}$.	Chezy's C ($A=25$).
0·1	0·0580	0·898	0·064	0·617	0·0358	0·0395	3·506	87·7
0·2	0·1650	1·288	0·128	1·000	0·1640	0·1280	4·017	100·4
0·4	0·4480	1·853	0·242	1·530	0·6840	0·3700	4·484	112·0
0·5	0·6160	2·080	0·295	1·730	1·0600	0·5100	4·618	115·2
0·6	0·7760	2·281	0·340	1·920	1·4900	0·6550	4·726	118·0
0·8	1·1710	2·733	0·428	2·220	2·6000	0·9520	4·888	122·0
0·836	1·2390	2·810	0·441	2·260	2·8000	0·9970	4·909	122·9
1·0	1·5710	3·142	0·500	2·450	3·8600	1·2250	4·999	124·9
1·2	1·9710	3·550	0·555	2·610	5·1500	1·4500	5·071	126·7
1·4	2·3660	4·002	0·591	2·720	6·4400	1·6100	5·117	127·8
1·6	2·6940	4·430	0·608	2·770	7·4500	1·6850	5·134	128·2
1·8	2·9770	4·995	0·596	2·740	8·1500	1·6320	5·122	128·0
2·0	3·1420	6·283	0·500	2·450	7·7000	1·2200	4·999	124·9

TABLE XIX.—U-SHAPED SEWERS (FORM NO. 1).

Height : 24 inches.
Slope : 1 in 1,300.
Area : 3·571 square feet.
Breadth : 24 inches.
Hydraulic mean depth : 0·500 foot.
Discharge : 8·784 cusecs.
Velocity : 2·46 feet per second.

Depth : feet.	Area : square feet.	Perimeter : feet.	Hydraulic mean depth : foot.	Velocity, V : feet per second.	Discharge : cusecs.	VR.	Log $\frac{VR}{\nu}$.	Chezy's C ($A=25$)
0·1	0·0580	0·898	0·064	0·617	0·0358	0·0395	3·506	87·7
0·2	0·1650	1·288	0·128	1·000	0·1640	0·1280	4·017	100·4
0·4	0·4480	1·853	0·242	1·530	0·6840	0·3700	4·484	112·0
0·5	0·6160	2·080	0·295	1·730	1·0600	0·5100	4·618	115·2
0·6	0·7760	2·281	0·340	1·920	1·4900	0·6550	4·726	118·0
0·8	1·1710	2·733	0·428	2·220	2·6000	0·9520	4·888	122·0
1·0	1·5710	3·142	0·500	2·460	3·8640	1·2300	5·000	125·0
1·2	1·9710	3·542	0·556	2·617	5·1580	1·4500	5·070	126·5
1·4	2·3710	3·942	0·601	2·754	6·5290	1·6500	5·130	128·2
1·6	2·7710	4·342	0·638	2·821	7·8200	1·8000	5·170	129·2
1·8	3·1710	4·742	0·669	2·953	9·3700	1·9700	5·200	130·0
*2·0	3·5710	7·142	0·500	2·460	8·7840	1·2300	5·000	125·0
2·0	3·5710	5·142	0·695	3·020	10·7800	2·1000	5·240	130·8

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* Closed top.

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The following comparison was then possible:

Mr. Essex.	Author.
Atmospheric discharge :	
24-inch circular section.*	24-inch circular section.
Fall 1 in 1,300.	Fall 1 in 1,300.
Discharge 8·15 cusecs.	Discharge 8·15 cusecs.
23-inch by 21-inch U-shaped section.*	24-inch by 24-inch U-shaped section (form No. 1).
Fall 1 in 1,090.	Fall 1 in 1,300.
Discharge 10·00 cusecs.	Discharge 10·78 cusecs.
Excess capacity of U-shaped section, 22·60 per cent. Mr. Essex quotes this as 12·25 per cent.	Excess capacity of U-shaped section, 32·2 per cent. Author's Tables I and III give 32·70 per cent. on Santo-Crimp formula.
Drowned discharge :	
24-inch circular section.*	24-inch circular section.
Fall 1 in 1,300.	Fall 1 in 1,300.
Discharge 7·74 cusecs.	Discharge 7·70 cusecs.
23-inch by 21-inch U-shaped section.*	24-inch by 24-inch U-shaped section (form No. 1).
Fall 1 in 1,090.	Fall 1 in 1,300.
Discharge 8·00 cusecs.	Discharge 8·78 cusecs.
Excess capacity of U-shaped section, 3·40 per cent. Mr. Essex quotes this as 10·30 per cent.	Excess capacity of U-shaped section, 14·0 per cent. Author quotes 13·80 per cent. on Santo-Crimp formula.

* Sections of equal area.

The comparisons quoted above clearly indicated that the Author's Tables, based on the Santo-Crimp formula, gave an accurate indication of the comparative values of the sections considered. In addition to that, it was clear that the application of Mr. Essex's method of calculation gave results which agreed to within 0·50 per cent. of the Author's Tables.

The adoption of a U-shaped section undoubtedly resulted in advantages with regard to self-cleansing velocities and permissible overloads before surcharging took place, together with uninterrupted passage of flows through manholes, with consequent improved efficiency of the sewer as a whole, and the Author was pleased to note that Mr. Essex appreciated those points.

Mr. Essex had discussed at some considerable length the relative merits and demerits of the formulas used in calculating discharges, both in pipes and in open channels, and whilst it was quite true to say that there were considerable discrepancies to be found between discharges calculated by different formulas, it was equally true that the selection of a formula was surely a matter for individual choice and inclination.

Mr. Essex proceeded to infer that the Author's choice of the Santo-Crimp formula was an unhappy one, and he then proceeded to quote Reynold's law of resistance, which he used to calculate the value of Chezy's

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C, and he then determined velocities and discharges by means of the old Chezy formula.

The formula used by Mr. Essex for design in sewers was apparently $V=25 \log \frac{VR}{\nu} . R^{\frac{1}{2}}S^{\frac{1}{2}}$, where V denoted the average velocity, R the hydraulic mean depth, S the inclination or slope, and ν the coefficient of kinematic viscosity. Alternatively, the Santo-Crimp formula could be re-stated as $V = 124R^{\frac{1}{6}}.R^{\frac{1}{2}}S^{\frac{1}{2}}$.

Upon the variation of those two formulas Mr. Essex sought to prove that the Tables prepared by the Author were misleading, and to do so he made reference to Papers written by himself and by Mr. F. C. Scobey. It appeared to the Author that Mr. Essex had confused the relative merits of forms of cross-section with the relative merits of different formulas. The criticism put forward by Mr. Essex had no foundation in fact, and the Author wished to express the opinion that the application of any particular formula affected only the actual size of sewer selected, and did not in any way affect relative merits of one form of section with regard to another. The Author wished to refer Mr. Essex to the following statement which appeared on p. 267 §: "It must be noted, however, that the powers to which the hydraulic means depths and the diameters are raised do affect these comparisons. The actual effect on the relative sizes of each particular section is, however, a small one, and since the Santo Crimp and Bruges formula is the one most generally used when considering sewer-sections, it is proposed to make the comparisons on that basis."

In summing up, Mr. Essex had enumerated certain points with regard to the Paper, and for the sake of clarity, the Author appended his remarks in the same order :—

(1) The discharge of the U-shaped section when flowing full exceeded that of a circular section of equal diameter by 13·8 per cent., the maximum discharge of a U-shaped sewer being 32·70 per cent. in excess of the maximum discharge of a circular sewer of equal diameter.

(2) It was not true to say that a U-shaped section never needed to become surcharged; indeed, unfortunately, by the very nature of things, there was always the possibility of any sewer becoming surcharged if the outlet were drowned. It was true to say, however, that the U-shaped section allowed a larger factor of safety in that regard than either a circular or an egg-shaped section.

(3) Mr. Essex again emphasized the advantages to be obtained from a U-shaped section with regard to dry-weather flows. His point with regard to the increase in capacity by the increase in height of the sewer was clearly indicated in *Fig. 1* (p. 268 §).

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§ *Ibid.*

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(4) The advantages to be obtained by increasing the height of the U-shaped section were very evident, and the Author was pleased to say that a scheme for the construction of Cutthroat Valley sewer, in Sunderland, with allowance for future enlargement, had been submitted to, and had been approved by, the Ministry of Health in 1936. The preparation of that particular scheme had involved the consideration of an initial drainage area of 619 acres, and a future drainage area of 1,188 acres, the selection of the two hydraulic gradients used involving very careful consideration.

(5) The Author found it difficult to believe that the construction of U-shaped sewers permitted easier inspection, unless they were of unusually small dimensions.

(6) The percentage savings in capital costs were shown in *Fig. 6* (p. 277 §), and were set out on p. 278 §.

Mr. C. B. Lea showed in Fig. 8 (facing p. 418) a chart based on an ingenious logarithmic plotting of the Manning formula. The method of plotting was particularly apt, as the values of Kutter's n were clearly indicated, thus enabling the chart to be used for almost any type of channel. The properties of particular sections, as shown in Table XVII (p. 418), could be prepared from the Author's Tables, and used in conjunction with Mr. Lea's diagram.

For some years past the Author had used a chart based on a logarithmic plotting of the Santo Crimp formula for sewer design. The Author's chart enabled the diameter and velocities of sewers to be read off when the values of the slope and capacity were known.

The Author wished to acknowledge the kindly advice and encouragement given to him by Mr. J. E. Lewis, Assoc. M. Inst. C.E., the Borough Engineer of Sunderland, with regard to the preparation of his Paper.

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§ *Ibid.*

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