Paper No. 6524

Uniform flow of water in alluvial channels†

by

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Discussion

Mr Peter Ackers (Principal Scientific Officer, D.S.I.R. Hydraulics Research Station, Wallingford), considered that the Author's use of the term "laminar" in describing flow in alluvial channels was incorrect. By analogy with the Reynolds number at the upper limit of laminar flow in pipes, turbulent flow would occur when $4\ VR/\nu$ exceeded about 2,300. Assuming water at about 15°C to be the fluid, this meant that flow was laminar only when $VR < 0{\cdot}7 \times 10^{-2}$ sq. ft/sec. Because the lowest value of VR in the tabulated data was about 0·9, it was inconceivable that laminar flow, within the usual meaning of the phrase, occurred in any of these canal systems.

76. There were a number of apparently contradictory statements in the Paper, which needed further explanation. For example, in § 14, the Author suggested that a "$V = cRS$" phase occurred when velocities were low and there was no bed movement; then, in § 19, it was said that a change from "$V = C\sqrt{RS}$" to "$V = cRS$" occurred in the flood season when more silt entered the canal, and discharges were greater.

77. The assumptions involved in the derivation of the silt-carrying capacity equation (§§ 37 and 72) appeared to have been as follows:

(i) Concentration of solids was proportional to the mean shear force on the boundary.

(ii) Shear force was proportional to the square of the mean velocity.

Had the Author any experimental evidence to offer in support of the former conjecture? The derivation of equations from first principles had merit only if those principles had a sound physical basis.

78. In one part of § 46, it was stated that $f = (V/V_0)^2$: later in the same paragraph, this was changed without explanation to $f = (V/V_0)$. Lacey was then cited in support of the relationship $(V/V_0) \propto 1/n$, whereas in fact he first suggested[8] that $n \propto f^{0{\cdot}2}$ where $f = (V/V_0)^2$, i.e., $n \propto (V/V_0)^{0{\cdot}4}$, later modifying this to $n \propto f^{0{\cdot}25}$, i.e., $n \propto (V/V_0)^{0{\cdot}5}$. Were there any printers' errors in this section? If not, could the Author please explain his algebraic manipulation?

79. The crux of this Paper was the Author's suggestion that two different flow conditions might be found, identified by their dissimilar resistance functions:

(i) $$V = 66{\cdot}5 \left\{\frac{RS}{m^{0{\cdot}2}}\right\}^{0{\cdot}5}$$

and (ii) $$V = 2525 \left\{\frac{RS}{m^{0{\cdot}2}}\right\}$$

The former was similar to the usual exponential formulae for flow in the rough-turbulent zone, but the latter form of equation was unexpected in this context. The experimental evidence in support of the idea of alternative equations was given in Tables 6 to 16, but its worth would have been more easily judged if V had been plotted against $RS/m^{0{\cdot}2}$. If this was done, however, it would be seen that the evidence in support of equation (ii) as opposed to (i) above was very tenuous indeed (Fig. 3). The very corner-stone of the Paper appeared to have little theoretical or experimental justification.

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† Proc. Instn civ. Engrs, vol. 21 (Jan. 1962), pp. 115–138

Sir Claude Inglis (Consultant, formerly Director, D.S.I.R. Hydraulics Research Station, Wallingford) wrote that although this Paper had been published in 1962, the ideas contained in it originated 19 years earlier in 1943, as a result of research work done by Mr D. P. Jethwani and his co-workers in 1942–43 in connexion with the design of canals for the then proposed Upper Sind Barrage scheme. By 1943, a large amount of data was available regarding the changes that had taken place in the Sukkur Barrage Canals since they were opened in 1932. These canals had been designed according to Kennedy's diagrams[24] and the data showed that the canals which took off from the left, concave, bank of the Indus upstream of the barrage, scoured violently. On the other hand, the right bank canals, which took off from the inside of the bend, silted their sides to start with, to form wide berms. This was followed by heavy accretion of silt on their beds in their head reaches. Had this not been checked, it would soon have led to the canals losing "command", with consequent reduction of the discharges entering their heads. To prevent this, a one-mile long "approach channel" was constructed upstream of the barrage, so designed that the "feeder channel" which supplied water to the canals, drew its supply from the outside of an imposed bend, thus deflecting bed-sand away from its entrance (ref. 1, pp. 51 and 217–45). This work led to the almost

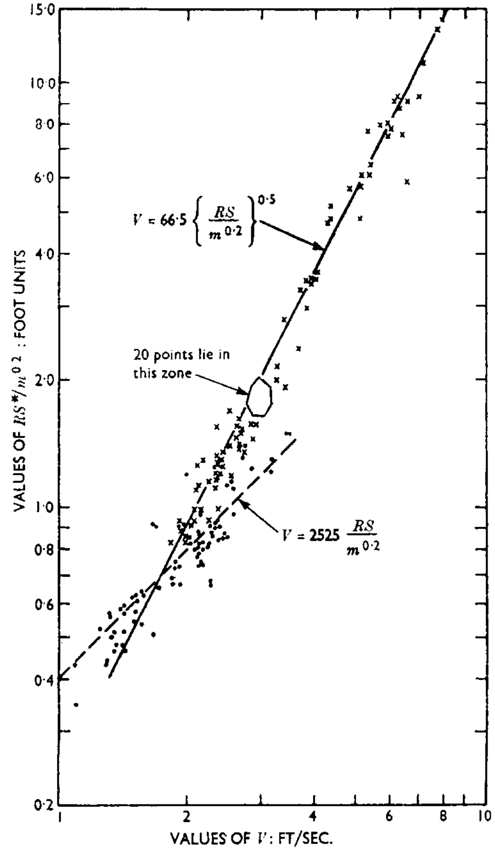

Fig. 3.—Sethna's resistance function

complete exclusion of bed-sand and a marked reduction of the suspended silt entering the canals. As a result, further accretion was prevented.

81. By 1939 it was realized that the Lacey formulae—which at that time were stated in terms of a single "f" value $=0{\cdot}75V^2/R$ and were based on Punjab canal data for channels with rippled beds of medium sand of 0·2 to 0·6 mm weighted diameters, did not give suitable dimensions for canals in Sind that had smooth beds and flat gradients and were generally considerably deeper and narrower than canals in the Punjab.

82. Mr Jethwani arrived at two main conclusions:

(i) There were two types of flow. In one type the bed was smooth and $V=2525RS/m^{0{\cdot}2}$, and in the other the bed was rippled and $V=66{\cdot}5\sqrt{RS}/m^{0{\cdot}1}$; and

(ii) width/depth ratios of 3 to 8 were suitable for Sind canals.

83. These conclusions were based on data for channels with (*a*) smooth beds consisting of grains predominantly finer than 0·10 mm, and (*b*) channels with material coarser than 0·2 mm with rippled beds, and there appeared to be no evidence that channels with bed grains less than 0·10 mm developed ripples, or that channels with bed grains coarser than about 0·2 mm were ever smooth. Mr Jethwani's conclusions were acceptable for smooth-bed channels of grains finer than 0·10 mm; but for sand beds coarser than 0·20 mm, the Inglis–Lacey formulae still held, though the single formula $V=66{\cdot}5\sqrt{RS}/m^{0{\cdot}1}$—which implied a wide range of permissible dimensions and slopes—was unacceptable for design purposes.

84. A point of great importance which the Author repeatedly stressed was that bed conditions in the Indus and at the heads of offtaking canals did not remain constant throughout the year, but varied widely. At the end of the "fair season" the beds were rippled, with "n" in Kutter's and Manning's formulae equal to about 0·030; but when the floods arrived, carrying a heavy charge of suspended silt, some of this silt deposited on and mixed with the bed material, the bed changing from ripples to a smooth bed—"n" decreasing to about 0·010.

85. There was nothing new in this concept, which the Author and others realized more than 20 years ago; but the Author had stressed the point more fully. What was so surprising was that having stressed this point so effectively, the Author then defined "silt" as "inorganic matter carried by water as bed load or in suspension"—thus confusing the whole issue. The Author still further confused the question by his §§ 26 and 27:

> "26. To check whether ripples were formed by the type of flow or were due to sand particles travelling down from above, ripples in a portion of the bed were obliterated by quickly smoothing with a small plank. Strict watch was kept on the movement of sand in the above reach which was found to be very slow. As soon as the plank was removed and the disturbance settled, ripples were seen again proving thereby that they were not formed by sand moving from above."

86. Though the Author was quite correct in saying that ripples were formed by the type of flow, he had overlooked the fact that the type of flow was determined under régime conditions by the three independent variables—discharge, size of bed grains, and the charge of bed material; so, though the Author's interpretation of this experiment might seem reasonable, it could only be true where the quantity of bed sand entering the channel was negligibly small. This was because unless the bed material that entered a channel during the year was carried forward, accretion would occur on the bed of the channel near its head, which in turn would lead to an increase in the slope until the bed material entering the channel was carried forward.

87. In 1942 Sir Claude Inglis had initiated experiments at the Hydraulics Research Station at Poona, to determine the effects of "charge of bed material" on the slope and dimensions of a channel. In these experiments, the same material as was laid in the bed of the experimental channel, was injected into a stream of clear water flowing with

constant discharge. Two series of experiments were run, with 1 cusec and 2 cusecs respectively. In each series, a low charge of 18 p.p.m. was injected to start with, the test being continued until stability was attained. The charge was then doubled, and the test again run to stability. This doubling of the charge was continued until meanders started to develop in the channel. When Sir Claude Inglis retired from India in 1945, the experiments were not continued with larger discharges, as had been planned; so the effect of "scale" on the coefficients in the various formulae was not accurately known; but in the Inglis-Lacey formulae for silted berms and medium sand beds of 0·2–0·6 mm, the Lacey coefficients for a weighted mean dia. of 0·43 mm and discharges exceeding 12 cusecs had been accepted.

88. In these formulae,

$$X = \frac{\text{the dry weight of bed material carried per cu. ft}}{\text{the weight of a cu. ft of water}}$$

Vs = the terminal velocity of the mean size grain falling through water,
ν = kinematic viscosity.
X, Vs, and ν are to be stated as ratios to the standard values (taken as unity) of $X=18$ p.p.m.;
Vs = terminal velocity of a grain of size 0·30 mm.
ν = value for viscosity of water at 15°C
Ws = surface width
$Dm = A/Ws$
m = weighted mean dia. of grains in mm.

Dimension	Inglis–Lacey formulae	Effect of grain size ($m \infty Vs$)
Ws	$= 2{\cdot}667\,\frac{Q^{0\cdot5}}{(g\cdot m)^{0\cdot25}}\left(\frac{XVs}{(\nu g)^{0\cdot33}}\right)^{0\cdot75}$	$\infty\ \frac{Q^{0\cdot5}X^{0\cdot25}}{\nu^{0\cdot083}g^{0\cdot33}}$
Dm	$= 0{\cdot}473\,Q^{0\cdot33}\left(\frac{m}{g}\right)^{0\cdot167}\left(\frac{XVs}{(\nu g)^{0\cdot33}}\right)^{-0\cdot33}$	$\infty\ \left(\frac{Q}{X}\right)^{0\cdot33}\frac{\nu^{0\cdot111}}{m^{0\cdot167}g^{0\cdot056}}$
	$S = \frac{g^{0\cdot083}m^{0\cdot417}}{1860Q^{0\cdot167}}\left(\frac{XVs}{(\nu g)^{0\cdot33}}\right)^{0\cdot583}$	$\infty\ \frac{X^{0\cdot583}}{Q^{0\cdot167}}\frac{m}{g^{0\cdot111}\nu^{0\cdot028}}$
	$V = 0{\cdot}79\,Q^{0\cdot167}g^{0\cdot417}m^{0\cdot083}\left(\frac{XVs}{(\nu g)^{0\cdot33}}\right)^{0\cdot083}$	$\infty\ \frac{X^{0\cdot083}Q^{0\cdot167}g^{0\cdot388}m^{0\cdot167}}{\nu^{0\cdot028}}$

Froude number $V\sqrt{g\cdot Dm}$ equivalent to $(XVs/(\nu g)^{0\cdot33})^{0\cdot25}$.

89. It would be noted that the equivalent Froude number formula, which Lacey had called the Inglis number, was independent of discharge and grain size except in the form Vs. It would also be noted that m cancelled out against Vs in the width formula; so that, as in the Lacey width formula, grain size was not a factor. In the slope formula, on the other hand, m and Xs combined to affect the slope, which varied directly as the first power of the grain size.

90. It was not found possible in the Poona experiments to determine the velocity of progression of grains of different diameter; but Mr G. H. Lean of the Hydraulics Research Station, Wallingford, had recently carried out experiments with radio-active tracers with a weighted mean diameter of 0·20 mm, which showed that with a discharge of 2 cusecs per ft width and a charge of 100 p.p.m.; grains of 0·20 mm progressed at 2 ft/hr; grains of 0·35 mm at 1 ft/hr; and grains of 0·10 mm at 10 ft/hr. Though these velocities might seem low, a velocity of 2½ miles per year was far from negligible.

91. The essential difference between the "Inglis–Lacey" formulae and the "Jethwani–Sethna" concept was that the former were régime formulae for channels with silted berms and rippled beds of medium sand, the régime being determined by the independent variables (discharge, bed-mix and bed-charge); whereas the Jethwani–Sethna concept was based on a single formula (whether the bed was smooth or rippled) and a width/depth range of 3 to 8; the "silt charge" including both suspended silt and bed-sand. This combination was quite meaningless, because the formulae had opposite effects at different times of the year.

92. The Author's concept was not in fact a "régime concept"; but a design concept with a range; and throughout the Paper he had used velocity and slope as though they were independent variables. From this, to believing that the steeper slopes found in the head reaches of most canals had been caused by the canals having been designed that way, was a short step, a point which the Author had endeavoured to establish—see, for instance, § 57, where he quoted Lacey: "It is important to note that if a main canal is excavated in the first instance to an excessive slope, it will . . . eventually achieve some kind of balance and remain stable. The slope, however, would be in excess of that . . . in a régime channel." While this might be true sometimes, it was not the usual explanation. The steep slope in the head reach might be due, in rare instances, as in the Jamrao Canal (§ 56) to the head reach of the canal having been excavated in dune sand, which was much coarser than the sand further downstream; but, usually, the steep slope in the head reach had been caused by the building up of bed-sand that had entered the canal in previous years. This build-up did not normally extend more than 10 to 20 miles down the canal; and ended abruptly at a point beyond which the slope was much flatter. This was due to the petering out of the effect of bed-sand entry and "sorting". This extremely complex question could not be dealt with here, but it was, in any case, obvious that bad design was not the reason for steep slopes in the head reaches of canals, from the fact that the Rohri Canal flattened its slope from 1 in 11,700 to 1 in 17,000, in spite of being excavated in tough material (§ 54).

93. The Author had referred to changes which occurred in the head portion of the Jamrao canal when it was opened in 1904. In 1906 Sir Claude Inglis was instructed by Mr Gebbie (later Sir Frederick Gebbie, Inspector General of Irrigation) to reduce the width in the head portion by 12 ft by constructing very strong, closely-spaced, porous groynes; but these were soon washed away, the channel re-establishing its natural régime width for the conditions of discharge and material exposed on the bed. The Author's idea that this régime was caused by the original designed slope being too steep was untenable.

94. At that time, Mr Gebbie issued stringent orders that the weir undersluices, situated just downstream of the head regulator of the canal, at the end of the "approach channel" from the Nara river, must never be open when the canal was drawing its supply; because this led to a heavy charge of bed-sand entering the canal, which caused higher levels in the canal. Recently, however, when the Jamrao weir was being remodelled, a large flow was passed through the undersluices. This led to large quantities of fine silt that had been accumulating upstream of the weir during the previous 50 years being thrown into suspension and carried into the canal. As a result, silt moving along the bed of the head reach reduced friction and the designed discharge was carried with a lower gauge. This improvement would only be temporary, and would cease when the store of deposited silt was exhausted. After this, there might even be a reversal to the conditions of 1904. This case was quoted to show how sensitive the head of a canal might be to an increase of sand entry, as in 1904, or of suspended silt, as in 1961.

95. Where, however, a heavy charge of coarse sand was temporarily washed into the head of a canal—particularly if the sand was coarser than that already in the head reach—permanent deterioration would result.

96. Having established beyond reasonable doubt that it was the material that entered the head of a canal that determined its régime, and that where a river course was stable and the heads of canals could be positioned at the outsides of bends—so that bed-sand and a considerable amount of suspended silt could be excluded—the canals could be designed and run with very flat slopes, as in the Sukkur Barrage canals.

97. It should next be considered whether success could be achieved elsewhere. In the case of Lower Sind Barrage, situated some 7 miles upstream of Kotri, success could have been achieved had the original silt-excluding design been adhered to when the barrage was constructed, about 1950, on the right bank of the Indus, mostly in the dry; the river being subsequently diverted through it, on an unnatural course.

98. As a result of this change—decided on to simplify construction and save some

capital expenditure—the efficiency of the canals had been seriously reduced for all time. In the Upper Sind Barrage Scheme, the reach of the Indus where it was to be built was highly unstable, the main channel swinging from bank to bank. For this reason, bed-sand could at best only be excluded from the canals on one bank. Had the slope of the country been less flat, this would not have been so serious; but actually much of the area could only be commanded for "flow irrigation" if smooth-bed flow conditions had been possible.

99. Farther to the north, in the Punjab, the sand in the rivers was progressively coarser; but owing to the slope of the land being steeper, medium-sand régime could generally be maintained—though this frequently necessitated the installation of ejectors. Under such conditions, steep slopes had developed in the head reaches of the canals. The most serious trouble occurred, of course, where a large proportion of the river flow was drawn off to supply the canals; so that any considerable amount of ejection was impossible. This should be compared with what the Author said in § 31, which read:

> "As far as canal designs are concerned bed-load is of no consequence since the intentions are always to design them on low values of Kutter's '*n*' where there is no bed movement."

Although this statement and some of the Author's other ideas were unacceptable, Sir Claude considered that the Paper should produce a very interesting and fruitful discussion, and if, as was to be anticipated, the Paper led to Mr Lacey producing a set of modified Inglis–Lacey formulae to fit the smooth-bed range in which m was less than 0·10 mm, this would be an important advance—particularly as smooth-bed conditions applied widely in Great Britain. Under such conditions, Vs varied as m^2, whereas in the medium sand range Vs varied approximately as m. In the transition range ($m > 0{\cdot}10 < 0{\cdot}20$) conditions were unstable and this grain size was not normally found on the beds of channels in which there was stable unidirectional flow. In estuaries and on the sea coast, however, where there were fluctuating tidal conditions, beds of this grain size were widely found.

Mr Gerald Lacey (Consultant, Sir M. MacDonald & Partners), wrote that this timely Paper, with its comprehensive range of observations, should prove of value to all workers in this field of research. The adoption of the two parameters, V/RS, and C, the Chézy coefficient as a basis of analysis was admirable, and a real advance, but the Author's contention that these two parameters, coupled with the weighted mean diameter of the sediment, m, provided a complete unified solution to the problem of flow in alluvium would not meet with ready acceptance. Those who had made a study of channels with loose sandy beds with ripple formation would find that the Sind data presented a very different problem for which the fineness of the transported sediment, and possibly cohesion afforded an explanation.

101. The Author had not plotted his data nor carried out a rigid statistical analysis demonstrating that his equations gave the best fit. A log plot of values of V/RS against size of bed particle, m, showed that there was very great "scatter"; it did, however, indicate a discontinuity between the Sind range of observations, with values of m varying from 0·02 to 0·13 and those for sandy bedded channels with values of m from 0·15 to 0·40. This suggested that the power of m assigned in the Paper, of 0·2 might be a variable rather than a constant. The writer had therefore made a close study of the Sind observations.

102. A reference to Table 8 showed that the observations on the Rohri canal were consistent. The mean value of V/RS for these fifteen observations was 4317, the maximum being 4854 and the minimum 3900. The indication was that in these channels the parameter V/RS was independent of the value of m.

103. The remaining seventeen miscellaneous Sind observations presented a different picture. The mean value of these observations of V/RS was 4200, but the maximum value was no less than 5332 and the minimum no more than 3021. It would be noted

that Serial Nos 26 and 29 both referred to observations on the Nasir Branch and both had the same value of m, namely 0·08. They should therefore perform equally well but the first had a value of V/RS of 3037 and the second of 4968. The equation $V/RS = 2525/m^{0\cdot 2}$ would imply that both channels should have produced a value of 4184. Such observations demanded scrutiny.

104. It was highly probable that the disparity in the recorded values of V/RS was caused almost entirely by difference in the "channel condition". The computed value of Manning's coefficient N was an excellent yardstick of channel condition when applied to channels said to be in the same class. Table 17 showed the results obtained.

TABLE 17

Serial No.	V/RS	C	N
26	3037	71·22	0·0283
29	4968	79·75	0·0213

105. These figures showed that the engineer would class the first channel as an "earth" channel in thoroughly bad condition with a rough bed—a bad case of one of the two forms of "positive shock". Such a channel with a cohesive ragged bed might well remain stable but was far from complying with "régime" requirements. The second channel was clearly in the engineer's "perfect" condition and it was such channels, rather than mere stable channels, which approached to the ideal of "régime". All such channels, it would appear, lay within a belt of observations of V/RS from 4000 to 5000, with few exceptions.

106. A study of Tables 6 and 7 showed that there were certain channels, discordant in their context, which conformed with the concept of optimum channel performance. Thus in Table 6, Serial Nos 17, 18, and 23 had values of V/RS of 4599, 4034, and 3932, respectively. Other examples would readily be detected. It was these channels which exhibited what the writer once termed negative shock associated with smooth banks and "possibly smooth rigid patches of the bed".

107. In Table 18 had been listed all the Rohri Canal observations, all the miscellaneous data which lay approximately within the range of V/RS between 4000 and 5000, and all the negative shock channels without exception. It would be observed that values of Chézy's coefficient C, and of the product (RV), as representing the Reynolds number had been computed.

108. The linear-resistance equation $V/RS = \text{constant}$, was usually associated with a mobile bed. The observations on the Sind canals suggested that with fine bed material the precise grade was immaterial. Thus, if there were no eddies to be shed, any sediment moved must move within the laminar boundary region. In a rigid channel with smooth boundaries the laminar boundary region shed no eddies within the range of smooth turbulence to which the Blasius equation applied. It would appear therefore that on the Sind canals transporting fine silt (as also on "negative shock" channels) the Phillips equation $V/RS = \text{constant}$, and the Blasius equation, $C = K(RV)^{0\cdot 125}$ should simultaneously apply.

109. In Fig. 4 the observations given in Table 18 had been plotted. Of the 32 observations all had been included but the four discordant channels had been omitted in the computation of the constants. The two resulting equations were:

$$C = 70\cdot 0(RV)^{0\cdot 125} \quad \ldots\ldots\ldots \quad (1)$$

and

$$V/RS = 4350 \quad \ldots\ldots\ldots \quad (2)$$

The fit of the first equation (see Fig. 3a) was in the circumstances somewhat remarkable. The way in which the "negative" shock channels conformed was satisfactory. A plot of this character, when the power was low, was not conclusive, and for this reason values

TABLE 18.—PHILLIPS-BLASIUS CORRELATION

Ref. No.	V/RS	(RV)	C	$(RV)^{0\cdot125}$	K	m
8/1	4152	29·84	108·2	1·529	70·77	0·050
8/2	4236	23·59	100·4	1·485	67·61	0·130
8/3	4263	24·03	101·4	1·488	68·15	0·130
8/4	3900	27·30	103·2	1·512	68·25	0·030
8/5	3914	27·40	103·6	1·513	68·47	0·030
8/6	4453	26·88	109·2	1·509	72·37	0·020
8/7	4445	26·73	108·9	1·508	72·21	0·020
8/8	4112	24·33	102·4	1·490	68·72	0·100
8/9	4144	23·95	102·6	1·487	69·00	0·100
8/10	4245	13·46	92·1	1·382	66·64	0·050
8/11	4292	13·45	92·9	1·385	67·08	0·060
8/12	4854	9·59	96·8	1·327	72·95	0·080
8/13	4755	9·10	94·0	1·318	71·32	0·040
8/14	4603	9·10	91·8	1·318	69·65	0·080
8/15	4387	24·81	123·2	1·494	82·46*	0·040
8/16	4331	24·70	121·9	1·493	81·65*	0·040
8/21	4354	10·03	95·4	1·334	71·51	0·080
8/22	4398	10·22	96·6	1·337	72·25	0·080
8/23	4304	15·23	99·3	1·406	70·63	0·080
8/24	4223	15·12	97·7	1·404	69·59	0·070
8/29	4968	2·88	79·7	1·141	69·85	0·080
8/30	4887	4·29	87·0	1·200	72·50	0·070
8/31	5051	2·31	81·0	1·111	72·91	0·070
8/32	3895	2·44	69·8	1·118	62·43*	0·090
6/15	4471	6·84	101·0	1·271	79·46*	0·263
6/17	4599	0·86	70·8	0·980	72·24	0·151
6/18	4034	1·65	73·5	1·065	69·01	0·186
6/23	3932	1·77	73·4	1·074	68·34	0·199
6/39	4016	2·32	75·0	1·111	67·51	0·199
6/40	4340	3·74	80·3	1·179	68·11	0·237
6/42	4268	1·84	80·3	1·079	74·42	0·178
7/21	4108	2·49	76·6	1·121	69·33	0·233

* Discordant.

Note.—Ref. No. 6/15 and Ref. No. 7/21 are identical and are duplications of one observation on the Nasrana distributary.

of the coefficient K had been plotted, so as to show any undetected trend, in Fig. 3b. Similarly values of V/RS (see Fig. 3c) had been plotted to show their approximate constancy within the entire range of Reynolds numbers.

110. There were thus two equations equally applicable to Sind conditions,

$$C = K(RV)^{0\cdot125}; \quad c = V/RS$$

which permitted V, R, and S to be eliminated at will. Thus

$$V = (K^2/c)^{1\cdot333}R^{0\cdot333} = 1\cdot172R^{0\cdot333}.$$

It was more convenient to compute V, R, and S in terms of (RV) as representing q the discharge intensity. These values were given in Table 19.

111. These equations for smooth turbulence were markedly different from those associated with loose, sandy, rippled beds. Finally it should be noted that Manning's rugosity coefficient, N, could be computed from the equation

$$N = 1\cdot4858c^{0\cdot167}/K^{1\cdot333} = 0\cdot0208 \quad . \; . \; . \; . \; . \; . \; . \quad (3)$$

This represented approximately the optimum performance of channels transporting fine sediment.

TABLE 19.—SIND 1962 EQUATIONS

Unit	Equations
Velocity, V	$1{\cdot}1264\ q^{0\cdot25}$
Hydraulic mean depth, R	$0{\cdot}8878\ q^{0\cdot75}$
Slope, S	$0{\cdot}0002917/q^{0\cdot5}$

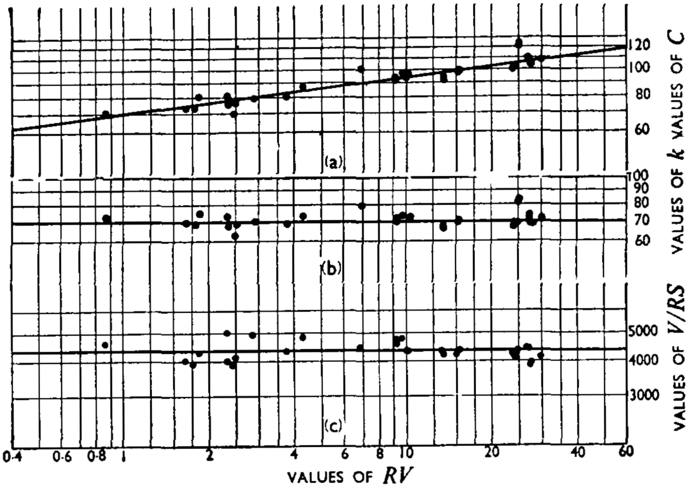

FIG. 4

112. Owing to the great scatter it was difficult to establish any equation of the form $V/RS = F''(m)$ when the range of m was small. Thus from Table 6, a value of m of 0·264 was associated with a value of V/RS of 3120 whereas a value of m of 0·263 was associated with a value of V/RS of 4471. This vitiated any arbitrary system of averaging. Omitting the abnormal channel it would be found that within the range of m of 0·261–0·280 were 12 channels in all with an average value of m of 0·2714, and of 3421·5 for V/RS, the maximum value of V/RS being 3688 and the minimum 3120. Employing the Author's equation to compute V/RS the close agreement of 3277·5 was obtained.

113. But if the régime equation $V/RS = 3100/f$ was employed, and if for f, its equivalent of $1{\cdot}76m^{0\cdot5}$ was substituted;

$$V/RS = 1760/m^{0\cdot5} = 3378$$

which agreed even more closely. Both equations gave identical results when the value of m was 0·300 which was not surprising because 0·300 was very close to the mass centre of the observations on sandy beds. It was, however, the power, whether 0·20 or 0·50 which was still in doubt.

114. There were unfortunately very few observations on channels with a mean bed-sand diameter of the order of 0·400 mm, except those which fell into the second class, channels with waves or dunes on the bed. The following two observations were of interest:

Ref. No.	m	V/RS	$1760/m^{0\cdot5}$	$2525/m^{0\cdot2}$
6/7	0·405	2562·5	2765·6	3025
7/6	0·398	2754·0	2790·0	3098

115. The first example was placed in the second class in the Paper, possibly as being less discordant in this class than in the first. The power of m of 0·5 gave a better fit.

116. The second equation $C=66{\cdot}5/m^{0{\cdot}1}$ had the defect that it had not been established. The Appendix was devoted to dimensional analysis and it was useful to apply the same process to the second equation. Without doing any violence to it this expression could have been re-written,

$$V = \text{const}\,(R/m)^{0{\cdot}1}(gRS)^{0{\cdot}5},$$

thus rendering it dimensionally homogeneous. Having reached this stage it would have been interesting to plot log values of C and R/m and to examine whether the power of 0·10 gave the best fit.

117. In Table 14 were entered 13 observations at the same site and all the values of V, R, and S^* were of the same order. The mean values were

$$V,\ 2{\cdot}930;\quad R,\ 6{\cdot}708;\quad S^*,\ 0{\cdot}2292;\quad m,\ 0{\cdot}4443.$$

In terms of the Manning-Strickler equation

$$V = 47{\cdot}53(R/m)^{0{\cdot}167}(RS)^{0{\cdot}5}.$$

Similarly for Table 16 there were the mean values

$$V,\ 2{\cdot}985;\quad R,\ 7{\cdot}669;\quad S^*,\ 0{\cdot}2025;\quad m,\ 0{\cdot}4389$$

and

$$V = 47{\cdot}02(R/m)^{0{\cdot}167}(RS)^{0{\cdot}5}$$

From Table 15 the mean values were

$$V,\ 2{\cdot}3425;\quad R,\ 4{\cdot}9925;\quad S^*,\ 0{\cdot}1894;\quad m,\ 0{\cdot}2587$$

giving a value of the constant in this instance of 44·16.

118. Finally since the roughness might depend more upon the geometry of the bed waves than on exact sand size it should be ascertained whether the value of C was merely a function of R.

119. The foregoing comments covered the more important aspects of the Paper. The limits of variation of the B/D ratio in Sind presented an unusual problem. Normally of régime channels transporting incoherent alluvium it could be said that the B/D ratio was a function of the discharge, large channels being relatively wide and shallow. In Sind it had been found that sections and gradients varied considerably for the same discharge but the great majority "run satisfactorily". The reason was that they transported fine silt for the greater part in suspension and that the bed and banks were cohesive. They were stable channels but not régime channels in the accepted sense.

120. The Jethwani equation involved an incorrect assumption. With low values of B/D it was quite incorrect to assume that D_m and R were practically equal to D. Thus with side slopes of $\frac{1}{2}$ to 1 in a small channel with a value of B/D equal to 4 it would be found that $D_m=0{\cdot}90D$, and $R=0{\cdot}72D$. Thus without regard to the fact that Table 4 could apply only to channels in cohesive material it was clear that it needed revision. Table 5 bore evidence that it had been computed for a constant value of B/D throughout. This value should be stated. Thus when B/D was a constant

$$A \propto D^2 \propto V^4$$
$$Q \propto AV \propto V^5;\ V \propto Q^{0{\cdot}2}$$

but SV was constant and hence

$$S \propto 1/Q^{0{\cdot}2}$$

121. As long as the ratio B/D was constant, values of D, D_m, and R bore a constant ratio to one another, otherwise not. Hence if the equation

$$S^* = 0{\cdot}52f^{0{\cdot}6}/Q^{0{\cdot}2}$$

was applied to the design of a canal system throughout this should logically imply a constant value of B/D throughout, a somewhat unusual procedure.

122. In conclusion, the Author's Paper should provoke further research in this field of hydraulics which had been somewhat neglected in the past.

Mr A. R. B. Edgecombe (Consultant), drew attention to the Author's reference to the Rohri Canal taking off upstream of the Lloyd (Sukkur) Barrage. The Author maintained that it started eroding its banks and scouring the bed because it was finally designed and excavated to a slope of 1 in 11,700 with a velocity of 3·50 ft/sec, which was considered higher than the safe velocity for Sind canals. "The result was that it started eroding the banks and scouring the bed till it ultimately attained a gradient of 1 in 17,000."

124. The design data for the Rohri Canal and the other canals taking off at Sukkur were given in Table 20. All these canals were taking off from a river (the Indus) where the Lacey silt factor was assessed as 0·9; but the slopes at which these canals were actually operated differed from the designed slopes. This was exemplified in Table 21.

TABLE 20.—DESIGN DATA FOR CANALS TAKING OFF AT SUKKUR

Name of canal (1)	Full discharge		Bed width: feet (4)	Slope (5)
	Kharif: cusecs (2)	Rabi: cusecs (3)		
Sukkur right bank canals:				
North Western	5,200	3,000	165	1 in 14,000
Rice	10,100	0	243	1 in 12,000
Dadu	3,250	2,200	93	1 in 11,500
Sukkur left bank canals:				
Eastern Nara	13,000	8.000	346	1 in 11,600
Rohri	11,000	9,900	247	1 in 11,700

125. The Rohri and Eastern Nara Canals took off on the outer curve of the Indus River at Sukkur. As a result silt was excluded from these two canals. They demonstrated the "secondary problems" referred to in the resolution of the 9th Research Committee Meeting of the Central Board of Irrigation, 11–15 July, 1939, on "Silt Excluders and Ejectors". It was interesting that a curvature of mean radius 11 times the bed width (for such was the curvature at Sukkur), could exclude bed silt so effectively.

126. On the opposite (right) bank conditions were very different. The North Western, the Rice, and the Dadu Canals took in large quantities of bed silt, although on only one occasion did they have to resort to draglines for clearance. That was on the North Western.

127. In view of the difference in functioning of these right bank and left bank canals it was somewhat disconcerting to find that the silt contents taken from turbulence downstream of the head regulators were very similar. Table 22 would corroborate this statement. The weights of silt in grammes/litre were averages for the years 1936, 1937, and 1938, from the register of daily records taken at Sukkur.

128. The Author stated: "For silt charge observation, samples taken from turbulence *D/S* of a regulator or fall will give reasonably reliable results." The samples which yielded the results in Table 22 were from turbulence downstream of the head regulators of the canals; from the middle span at one-half the full depth. But it appeared the bed load was not trapped.

129. The Author had deduced that $f=$ grammes per litre$/8{\cdot}95m^{0{\cdot}2}$. The Sukkur observations for silt content did not include the median diameters. Nevertheless, it was interesting to apply the records given in Table 23.

TABLE 21.—OPERATING SLOPES OF CANALS TAKING OFF AT SUKKUR

Date 1940		N.-W. Canal	Rice Canal		Dadu Canal			Eastern Nara Canal			Rohri Canal			Remarks
		Head to 83,824 (1 in)	Head to 25,000 (1 in)	Head to 80,000 (1 in)	Head to 5,000 (1 in)	5,000 to 10,000 (1 in)	10,000 to 26,000 (1 in)	Head to 5,000 (1 in)	5,000 to 10,000 (1 in)	10,000 to 26,000 (1 in)	Head to 5,000 (1 in)	5,000 to 10,000 (1 in)	10,000 to 26,000 (1 in)	
(1)		(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
May	28	—	—	—	16,700	7,700	11,500	—	—	—	15,200	15,600	53,300	—
May	30	17,427	—	—	—	—	—	—	—	—	—	—	—	—
June	11	—	—	—	12,500	16,700	10,000	—	—	—	15,200	18,500	64,000	Heavy silt charge in river
,,	15	13,832	—	—	—	—	—	—	—	—	—	—	—	
,,	25	—	—	—	16,700	10,000	10,000	—	—	—	17,900	13,500	64,000	
,,	27	—	—	—	—	—	—	16,700	17,100	10,000	—	—	—	
,,	29	14,183	—	—	—	—	—	—	—	—	—	—	—	
July	9	—	—	—	16,700	16,700	10,000	—	—	—	21,700	11,900	64,000	
,,	11	—	—	—	—	—	—	25,000	16,700	10,000	—	—	—	
,,	13	13,390	—	—	—	—	—	—	—	—	—	—	—	
,,	14	—	9,800	10,300	—	—	—	—	—	—	—	—	—	
,,	23	—	—	—	—	—	—	—	—	—	17,900	15,600	64,000	
,,	25	—	—	—	—	—	—	25,000	7,100	10,000	—	—	—	
,,	27	13,719	—	—	—	—	—	—	—	—	—	—	—	

Aug. 6	—	—	—	16,700	10,000	10,000	—	—	—	—	—	—	
,, 10	13,832	—	—	—	—	—	—	—	—	—	—	—	
,, 20	—	—	—	12,500	10,000	10,000	—	—	—	—	—	—	
,, 22	—	—	—	—	—	—	25,000	6,700	10,000	—	—	—	
,, 28	13,077	—	—	—	—	—	—	—	—	—	—	—	
Sept. 3	—	—	—	14,000	10,000	10,000	—	—	—	15,200	10,600	64,000	—
,, 5	—	—	—	—	—	—	20,000	7,700	10,000	—	—	—	—
,, 7	12,976	—	—	—	—	—	—	—	—	—	—	—	—
,, 17	—	—	—	12,500	10,000	9,500	—	—	—	17,900	8,000	64,000	—
,, 19	—	—	—	—	—	—	20,000	7,100	10,000	—	—	—	—
,, 21	14,570	—	—	—	—	—	—	—	—	—	—	—	—
Oct. 1	13,832	—	—	12,500	10,000	9,500	—	—	—	17,900	9,600	64,000	—
,, 3	—	—	—	—	—	—	16,700	7,700	10,000	—	—	—	—
,, 12	15,494	—	—	—	—	—	—	—	—	—	—	—	—
,, 15	—	—	—	25,000	6,250	9,500	—	—	—	21,700	13.500	64,000	—
,, 17	—	—	—	—	—	—	16,700	6,700	10,000	—	—	—	—

TABLE 22.—WEIGHT OF SILT IN CANALS: GRAMMES/LITRE

Canal (1)	May (2)	June (3)	July (4)	August (5)	September (6)	October (7)
North Western	2·681	3·847	3·808	3·699	2·426	1·074
Rice . . .	2·902	3·855	3·773	3·818	2·465	1·012
Dadu . . .	2·826	3·775	3·902	3·509	2·346	0·872
Eastern Nara	2·607	3·663	3·712	3·874	2·417	0·847
Rohri . . .	2·457	3·586	3·584	3·918	2·442	0·957

TABLE 23

Canal (1)	Site (centre of bed) (2)	Date of observation (3)	Mean diameter from the Vidhyanathan optical lever siltometer: mm (4)	Observers (5)	Remarks (6)
North Western	2,000 ft downstream of head regulator	8 Feb., 1941	0·3048	Mr A. R. B. Edgecombe Mr G. N. Mirchandani	Canal running
North Western	R.D. 84,000	12 Feb., 1941	0·1880	Mr A. R. B. Edgecombe Mr G. K. Ajwani	Canal running
Rice . . .	500 ft downstream of head regulator	8 Feb., 1941	0·3822	Mr A. R. B. Edgecombe	Canal closed
Rice . . .	R.D. 80,000	12 Feb., 1941	0·1578	Mr A. R. B. Edgecombe	Canal closed
Dadu . . .	R.D. 80,000	13 Feb., 1941	0·2158	Mr A. R. B. Edgecombe Mr G. K. Ajwani	Canal running

North Western Canal	grammes per litre (Table 22, July)	3·808
	m (Table 23)	0·3048
	$f = 3{\cdot}808/8{\cdot}95 \times 0{\cdot}3048^{0{\cdot}2}$	0·5
Rice Canal	grammes per litre (Table 22, July)	3·773
	m (Table 23)	0·3822
	$f = 3{\cdot}773/8{\cdot}95 \times 0{\cdot}3822^{0{\cdot}2}$	0·5
Dadu Canal	grammes per litre (Table 22, July)	3·902
	m (Table 23)	0·2158
	$f = 3{\cdot}902/8{\cdot}95 \times 0{\cdot}2158^{0{\cdot}2}$	0·6

130. These values of f would entail a slope of 1 in 24,380 in the North Western, 1 in 27,240 in the Rice, and 1 in 16,630 in the Dadu. Such slopes were very much flatter than the designed slopes, and, with the exception of the Dadu Canal in the head

reach, considerably flatter than the slopes at which they had to be run in practice to avoid silt accumulation.

Mr G. A. M. Brown (formerly Chief Engineer, Indian Irrigation Service) wrote that the Author appeared to regard a channel as stable only when the velocity obtained from the régime turbulence criterion V^2/R was the same as that obtained from his flow formula $V=cRS$. His criterion for stability was thus $VS=4f/3c$.

132. He did not appear to regard $S=4f/3C^2$ obtained, in a similar manner, from the Chézy formula $V=C\sqrt{RS}$, as an equally valid criterion for stability, yet the point at which both these criteria were satisfied simultaneously should be the point of transition from one flow pattern to the other, and ought to be within the zone of stability. This point should be reached when V attained the value $C^2/c=1{\cdot}75$ ft/sec.

133. The Author's third flow equation $V=1{\cdot}346/0{\cdot}0225f^{0{\cdot}25}R^{0{\cdot}75}S^{0{\cdot}5}$ provided not only a further criterion of stability, but a régime flow formula in which his conditions for stability were implicit. By putting $0{\cdot}75V^2$ for fR in this equation one obtained the slope criterion $SR^{0{\cdot}5}=3100f^{0{\cdot}5}$ and the régime formula $V=3100RS$.

134. The data, however, would appear to make the constant nearer 3,500 for Punjab canals, and 4,250 for Sind, and, from this, one could infer that the index of "f" in the third equation required further investigation.

135. Table 24 compared the Author's conditions for régime or stability with those of Lacey, Blench, and King.

136. Since the Blench–King régime flow formula corresponded to the smooth turbulent stage of flow—the Blasius line in "pipe" flow—it would appear that the Author envisaged stability only when flow was near the point of transition from laminar to smooth-turbulent flow.

137. It would also appear that a channel with a flow pattern of $V=cRS$ would satisfy Mr Sethna's criterion for stability only for one particular value of the silt grade (for $m=0{\cdot}20$ when $V=3500RS$, or $m=0{\cdot}014$ when $V=4250RS$), while one with a flow pattern $V=C\sqrt{RS}$ would be stable when V was inversely proportional to $m^{0{\cdot}2}$ ($Vm^{0{\cdot}2}=1{\cdot}265$ or $1{\cdot}04$ when $V=3500RS$ or $V=4250RS$, respectively, and when m had the value of 0·20 or 0·074, the velocity = 1·75 ft/sec. and the flow pattern was at the point of transition from $V=cRS$ to $V=C\sqrt{RS}$).

138. Having specified his flow formula and criteria for stability the Author then proceeded to develop his slope/discharge formula $S^*=0{\cdot}52f^{0{\cdot}6}/Q^{0{\cdot}2}$ and, finally, to suggest rules for the design of canals based on this formula, without specifying any definite criterion for width.

TABLE 24.—COMPARISON OF CONDITIONS FOR STABILITY

	Criterion for stability	Régime formula	VS relationship
Lacey . . .	$R^{0{\cdot}5}S \propto f^{1{\cdot}5}$	$V \propto R^{0{\cdot}667}S^{0{\cdot}333}$	$VS \propto f^2$
Blench* . .	$D^{0{\cdot}5}S \propto f^{0{\cdot}75}$	$V \propto D^{0{\cdot}833}S^{0{\cdot}667}$	$VS \propto f^{1{\cdot}25}$
King . . .	$D^{0{\cdot}5}S^{0{\cdot}917} \propto f^{0{\cdot}625}$	$V \propto D^{0{\cdot}9}S^{0{\cdot}733}$	$V^{1{\cdot}091}S \propto f^{1{\cdot}227}$
Sethna . .	$D^{0{\cdot}5}S \propto f^{0{\cdot}5}$	$V \propto DS$	$VS \propto f$

* Assuming Blench's f_B/f_S to be a constant.

139. At first sight it might appear that Mr. Sethna was advocating a slope/discharge relation in which the slope varied as the fifth power of the discharge instead of the sixth. This was not, however, really so. It was due to the Author having had to use B/D as a parameter in order to express S, W, D in terms of Q, and it would not have occurred had he used a simpler width relationship. It had obscured the fact that the constant 0·52 in his slope formula was not really a constant, but a function of the parameter B/D, which itself was a function of Q. It would also appear to have caused Mr Sethna to

attach more significance to the minimum values for slope obtained from his formula, than they would appear to warrant. They were, in fact, caused by the geometry of the section. The value of the parameter B/D which made the slope a minimum for a particular discharge, could be determined directly from the following relationship, which expressed B/D in terms of the side slope ratio N, where the side slope was N horizontal units to one vertical.

$$B/D = 4\sqrt{N^2+1}-5N+\sqrt{31N^2-30N\sqrt{N^2+1}+16}.$$

140. The range of minimum slope from 3 to 8 to which the Author referred, corresponded to the commonly used side slopes.

141. The corresponding values derived from the above formula were given in Table 25.

TABLE 25.—VALUES OF $x=B/D$ AND Ks IN THE FORMULA $S^*Q^{0\cdot2}=Ksf^{0\cdot6}$ TO GIVE THE MINIMUM SLOPE WHEN THE SIDE SLOPE RATIO N HAS THE VALUES, 0, ½, AND 1

Side slope ratio: N	B/D ratio: x	$f(x)$	Value of $Ks=1188\ f(x)/K$ when $K=V/RS$ has the values below		
			$K=3500$	4000	4250
0 (*a*)	8	1·89	0·642	0·562	0·529
½ (*b*)	4·61	1·76	0·598	0·522	0·492
1	2·8	1·675	0·569	0·497	0·468

(*a*) Vertical sides. (*b*) The side slope commonly used for design.

142. If, instead of using B/D as a parameter, the Author were to use another of Mr Lacey's criteria for stability, viz: his first and most original concept, and probably the most widely authenticated and accepted, $P=K\sqrt{Q}$ he would now have the same simple straightforward method of designing stable canals, according to his own concept of régime slope, as others had of designing them according to Lacey's concepts.

143. Putting the values of $P=8/3\sqrt{Q}$ and $R=3V^2/4f$ in the expression $Q=VPR$, gave $4V^6=f^2Q$. From this, and the Author's velocity/slope relation $VS=4f/3K$ —where K was 3500, or thereabouts, for Punjab canals, and 4200 for Sind ones—the relation $S^*Q^{0\cdot167}=(1680/K)f^{0\cdot667}$ was obtained; a relation which was not only independent of the B/D ratio, but from which the slope could be calculated in a simple and direct manner, without the necessity of employing any reservations or limitations regarding minimum slope.

Mr A. Kumar (Institute of Technology, Ranchi; now Post-graduate student, Imperial College of Science and Technology, London) congratulated the Author, for correlating the coefficients of friction, in both the linear and quadratic law of resistance, to the grain diameter.

145. However, no physical parameter specifying the range of validity of the linear law had been given.

146. It was not clear what "m"—the grain diameter designated. It would be helpful to know if it was m_{10}, m_{60}, m_{90} of the grain size analysis curve.

147. For the sake of universality and comparison Mr Kumar suggested that c and C should be rendered non-dimensional, e.g. $[K_1=c\nu^{0\cdot333}/g^{0\cdot667}]$ and $[K_2=C/\sqrt{g}]$; various equations could then be rendered non-dimensional as for $V=cRS$

$$V = K_1\cdot\left[\left(\frac{gR^3}{\nu^2}\right)^{0\cdot167}\cdot S^{0\cdot5}\right]\cdot g^{0\cdot5}\cdot R^{0\cdot5}\cdot S^{0\cdot5} \quad . \quad . \quad . \quad . \quad (4)$$

and for $V=C\sqrt{RS}$

$$V = K_2\cdot g^{0\cdot5}\cdot R^{0\cdot5}\cdot S^{0\cdot5} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

And fitting a Chézy type equation for equation (4)

$$\frac{C}{\sqrt{g}} = \left(\frac{c\nu^{0\cdot333}}{g^{0\cdot667}}\right)\cdot\left(\frac{gR^3}{\nu^2}\right)^{0\cdot167}\cdot S^{0\cdot5} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

a result which, unless one agreed with the "laminar flow thesis" looked strange, for C depended on $\sqrt{RS}$. Parameter (gR^3/ν^2) was worth investigating because similar functions had been used for scour initiation and time-scale determinations.

148. Using the Author's analysis $C = 2525/m^{0\cdot2}$ a non-dimensional form could easily be evolved.

$$C = \frac{K_1\cdot g^{0\cdot667}}{\nu^{0\cdot333}} = K'\cdot\left(\frac{\nu^2}{gm^3}\right)^{0\cdot0667} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where

$$K' = \frac{2525g^{0\cdot0667}}{\nu^{0\cdot133}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and finally for $V = cRS$

$$V = \left(\frac{K'\nu^{0\cdot0667}}{g^{0\cdot4667}}\right)\left[\left(\frac{gm^3}{\nu^2}\right)^{0\cdot133}\cdot\sqrt{\frac{RS}{m}}\right]\cdot g^{0\cdot5}\cdot R^{0\cdot5}\cdot S^{0\cdot5} \quad . \quad . \quad . \quad (9)$$

Similarly for $V = C\sqrt{RS}$

$$V = \frac{K''}{\sqrt{g}}\cdot\left(\frac{\nu^2}{gm^3}\right)^{0\cdot10}\cdot g^{0\cdot5}\cdot R^{0\cdot5}\cdot S^{0\cdot5} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where

$$K'' = \frac{66\cdot5\cdot g^{0\cdot033}}{\nu^{0\cdot0667}}$$

In both equations (9) and (10) Chézy's coefficient was a function of (ν^2/gm^3). Incidentally Professor C. M. White[25] had used the function in his analysis of data on stable channels in determining non-dimensional equations.

149. Equations (9) and (10) were developments of the Author's equations, assuming their correctness. These forms were suggested in view of their structure which pointed out significant parameters seeking to explain the mechanics of flow. Attention to the parameters might lead to a rationalized theory.

150. In § 14, page 171, the Author stated the reason for adopting the equation $V = cRS$ as the intactness of the boundary layer and hence the laminar flow. However, the high Reynold's number $(N = 4RV/v)\cdot 10^5$ to 10^7 prevailing in the channels showed that the flow was turbulent. Intactness of the boundary layer as determined by the ratio $m/\delta < 1$ signified laminar flow at the base only, but not the main flow in the channel which, for the case $m/\delta \ll 1$ was smooth-turbulent. Equation $V = cRS$ signifying the linear law of resistance was therefore misleading, although it was tempting to use it in view of the relation of c with m.

151. The ratio m/δ had been worked out from the data of Tables 6, 7, and 8; and it was found to vary from 0·08 to 2·6. Using Nikuradses[26, 27] data specifying smooth flow for $m/\delta < 0\cdot25$, rough flow for $m/\delta > 8$ and a transitional flow in between, it was found that the data in the Paper was partly for smooth flow and partly for the transition zone.

152. As could be derived from dimensional analysis $C/\sqrt{g}$ was a function of R/δ for smooth flow. Values of $C/\sqrt{g} = \{1/\sqrt{g}(V\cdot V/RS)^{0\cdot5}\}$ and R/δ were computed from the tables $\{\delta = 11\cdot6\nu/\sqrt{gRS}$; $v = 1\cdot084\times10^{-5}$ ft^2/sec. at 20°C which had been assumed as the prevailing temperature$\}$. For cases where $m/\delta < 0\cdot25$ it was found that

$$\frac{C}{\sqrt{g}} = -11\cdot5 + 7\cdot4\log\frac{R}{\delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

This equation on further inspection was found to be applicable up to $m/\delta < 1$ (though nearer to ratio 1, the transition-zone equation should be used). The coefficient 7·4 agreed with Powell's[28] solution which was derived from Keulegan's[29] analysis with additional data of his own.

$$\frac{C}{\sqrt{g}} = \frac{42}{\sqrt{g}} \log \frac{N}{C} \qquad (12)$$

$$(42/\sqrt{g} = 7{\cdot}4)$$

153. In the region of transition $m/\delta > 0{\cdot}25 < 8$, $C/\sqrt{g}$ should be a function of N and R/K. Such a function was suggested by Colebrook and White[30] for pipes and could be stated as:

$$\frac{C}{\sqrt{g}} = 6{\cdot}61 + 5{\cdot}76 \log \frac{R}{K + \delta/3{\cdot}5} \qquad (13)$$

In view of the coefficient 7·4 deduced from smooth flow (equation 11), one would expect for the present data

$$\frac{C}{\sqrt{g}} = A + 7{\cdot}4 \log \frac{R}{m + \delta/n} \qquad (14)$$

Where A = constant, and n = number.

154. The occurrence of transition in the data under consideration could be shown in a conventional manner by plotting $(C/\sqrt{g} - 7{\cdot}4 \log R/m)$ against m/δ. This graph was plotted, for the values of $m/\delta < 0{\cdot}6$ the graph was a straight line indicating smooth flow; for values of $m/\delta > 0{\cdot}6 < 2{\cdot}6$ the graph was a curve showing transition.

155. The function for the transition, could be written as

$$\frac{C}{\sqrt{g}} = -11{\cdot}8 + 7{\cdot}4 \log \frac{R}{m + \delta/8} \qquad (15)$$

Actually this equation was valid for m/δ up to 1·8 beyond which, the deviation from it was significant. For values of $m/\delta > 1{\cdot}8$ it was possible that

$$\frac{C}{\sqrt{g}} = A_1 + 7{\cdot}4 \log \frac{R}{m} \qquad (16)$$

This form was suggested by analysis of the few data available in the table.

156. The transition zone function was found to be similar to one suggested by Powell.[28]

157. The bed movement could be treated on the lines of A. Shields. This involved investigating the functional relationship between $\tau_0/(\omega_S - \omega)m = RS/(\rho_S - \rho)m = RS/1{\cdot}65m$ (assuming ρ_S to be 2·65) and m/δ by plotting one against the other.

158. Such a diagram showed in the region $m/\delta < 0{\cdot}25$ a straight, sloping line indicating laminar flow at the base; and from $m/\delta > 0{\cdot}6$ to 2·6 an upward-sloping curve indicating bed unevenness. $\beta = \tau_C/1{\cdot}65m$ (which in Shield's case was 0·04) could be roughly stated as 0·25; this value was quoted by S. Leliavsky as being valid for ripples in self-formed channels[31].

159. Bed movement did occur even when the boundary layer was intact, in this case it was due to viscous action. This was clear from Professor White's[32] experiments —the slow-speed case where $V_*K/\nu < 3{\cdot}5$.

The Author, in reply to Mr Ackers, referred him to "Fluid mechanics" by Dodge and Thomson: "There is abundant evidence that flow in channels is laminar at low velocities. It is not possible to predict this limiting value for laminar flow in channels by comparison with Reynold's criterion for pipes as laminar flow is known to exist at much greater velocities in channels than in pipes of same hydraulic radius. The loss of resistance in laminar flow is proportional to velocity." It would have been more correct for the Author to say in § 14 "The flow is laminar at the boundary layer".

161. There was nothing contradictory in the statements. The high discharge when $V=cRS$ applied was due to the fact that the friction was proportional to velocity as compared to the case where $V=C\sqrt{RS}$ applied and friction varied as the square of the velocity.

162. The assumptions involved in the derivation of the silt-carrying-capacity equation were based on textbooks, particularly Dodge and Thomson.

163. An omission from the fifth and sixth lines of § 46 was regretted. These expressions should read $f\alpha\left(\frac{V}{Vo}\right)^2\alpha\frac{1}{n^4}$ i.e. $n\alpha\frac{1}{f^{0\cdot25}}$.

164. Mr Ackers' remarks in § 79 were answered by the Author in his reply to Mr Lacey.

165. Mr Lacey had realized correctly that for lower values of "f" the constant (3100) required to be changed, and to make that change had kept "f" in the denominator. But when equations were derived by combining this equation with the equation suggesting the silt-carrying power of water namely $V=1\cdot17\sqrt{fR}$ or $1\cdot15\sqrt{fDm}$ (to replace the original Kennedy concept) the power of "f" changed which could be seen from the table given above.

166. The reason, why the original Lacey equations seemed to fit most of the data from the Upper Punjab and United Provinces, was that wherever the bed material varied between 0·3 and 0·4 and where the value of "f" was nearly one, the difference was not noticed because unity or nearly unity raised to any power was unity or nearly unity.

167. When the formula came to be tested for the Lower Punjab and Sind Canals where "f" or in the old Kennedy concept $\left(\frac{V}{Vo}\right)^2$ varied from 0·5 to 0·8 the difference became considerable and the Lacey formula gave different values of "f" from different formula.

168. In this Paper the correction in the value of the constant "c" had been suggested, basing it on the silt diameter and the corresponding Froude's coefficient of friction. The result of this change had been that the value of "f" obtained from any of the derived equations now was consistent and no ambiguity existed. The "f" now more or less corresponded to $\left(\frac{V}{Vo}\right)^2$.

169. Mr Lacey had always adopted his absolute rugosity coefficient as $0\cdot0225f^{0\cdot25}$ which would always be less than 0·0225 except where $f=1$. When $n=0\cdot0225$ and less, the bed was never in ripples and whenever the bed was in ripples the Kutter's "n" was always found to be more than 0·025.

170. The following quotations clearly showed that the value of "n" was low when the bed was not in movement and the value changed suddenly as soon as the bed material began to move, indicating that when the bed was not in movement, one law applied and while the bed was in movement, another law applied.

171. Herring and Trautwine in their translation of Kutter's paper pp. 53–55 had written: "*For instance in case of river beds covered with boulders and detritus we must* not overlook the fact that when the water is low and in general when the material forming the bed is not in motion there is much less resistance to the flow than when it is moved during floods. In the first case . . . the coefficient of roughness would be comparatively low, in the second case . . . a considerable portion of the energy of the stream is absorbed in carrying detritus forward and the coefficient of roughness may become quite large."

172. Mr J. Williamson* had stated: "The value of 'N' appeared to remain sensibly constant in a channel up to the point at which erosion began to take place. As soon

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* Min. Proc. Instn civ. Engrs, vol. 229, 1929–30, p. 348.

as erosion set in there was a *sudden* and irregular increase in the resistance due to the work expended by the current on the bed."

173. Contributors to the discussion had doubted whether the monomial equation $V=cRS$ could be applied even where the bed was smooth and not rippled, whereas Inglis (§ 91) and Lacey (§ 108) had said that their formulae were for flow with mobile rippled bed. Would they reconsider their concept in view of the Discussion on this Paper?

174. Between 1936 and 1943 many engineers started re-grading channels on Lacey's theory; there was confusion about which "*f*" was to be adopted, and every one started giving his own interpretation, usually contrary to what Mr Lacey would have imagined. As a result, much Government money was wasted in wrong silt clearance and the canal régime was upset. The central idea of the Paper was to give a reasonable yardstick on which engineers could base their findings and re-grade canals or design new ones without loss of public money.

175. As already stated in §§ 52 and 58 the formula $V=\frac{66\cdot5}{m^{0\cdot1}}\sqrt{RS}$ was not intended for design of canals.

176. Sir Claude Inglis might remember that his staff of Poona Research Station had worked out Kutter's "*n*" for the Sukkur Right Bank Canals when they were silting heavily prior to the silt-exclusion device coming into force, and the value of "*n*" was very low. After the silt had all been scoured away and before the new season's silt could enter Rice Canal, the designed discharge could not be passed through it at the designed gauge, and the gauge had to be raised by 1·2 ft above the design level before the canal could take its correct discharge. This resulted in steepening the gradient in the head reach considerably. Here the canal was not silted and no silt had to be scoured and yet the gradient steepened.

177. If it was to be taken, as Sir Claude said, that the fine silt was carried away leaving coarser material on the bed which needed the steeper gradient, the same phenomenon should have occurred in the two adjacent canals Dadu and North Western. Mr Edgecomb in his discussion had kindly given the silt charge, the diameter of the bed sand and the working gradients and it was quite clear that the bed material in the three channels was very nearly the same and so also was the silt charge but the energy gradients were different. Rice Canal gradient, looking to its discharge, was very steep compared with the other two canals, and it was this steep gradient (excess energy) which brought the bed material into movement and increased resistance in the flow to correspond to the $V=C\sqrt{RS}$ type.

178. As soon as the Barrage gates were opened due to an incoming flood, higher discharge was passed for the same gauge as already stated in § 19.

179. All the Punjab canals where Kutter's or Manning's "*n*" was more than 0·025, came under the $V=C\sqrt{RS}$ category.

180. The suggestion in § 91 that the formulae had opposite effect at different times of the year was only applicable to rivers where the conditions changed from season to season, but not to canals where the gradients did not alter (or if they did, it was only in channels which had gradients on the margin of applicability of the two formulae). To all the Punjab canals, United Provinces canals as well as Sind Canals like Nara, Jamrao, Desert and Begari which had steep gradients and where Kutter's "*n*" was much higher than 0·025, the quotation given in § 57 was applicable. Originally most canals were designed considering Chezy's "*C*" as 80. How that was chosen is not known, but according to Table 3 it was suitable for fine sand with rippled beds.

181. The Rohri Canal had not been excavated in tough material as assumed. It was the Rice Canal which was excavated in comparatively tough material. Rohri Canal was excavated in very friable soil and below R.D. 75000 it was running in high embankment. Earth for the banks was borrowed from the bed with the result that when the canal was opened the water level downstream of 72000 bridge remained low

and there was fall in water level at the bridge. In addition, due to the softer patches giving way, the canal had widened out in belly shape approximately a mile apart and formed deep scour holes 30 to 40 ft below designed bed level. Only at R.D. 20000 there were two clay lenses in a total length of about 1,000 ft which were artificially helped to scour away.

182. The pavement at the bridges was kept 2 ft below designed bed which also helped in re-grading.

183. In Table 8, the velocities observed for items 25 and 26 were definitely under-measured as could be seen in comparison to items 24, 27 and 28 and that was the reason why $\frac{V}{RS}$ worked out very low compared to $\frac{2525}{m^{0{\cdot}2}}$.

184. As stated in § 7 Lacey's suggestion, the diameter of the bed silt was correlated to Froude's coefficient of friction and the formulae were purely empirical. The actual diameters to which Froude had carried out his experiments was not known, though in the original paper published in the Proceedings of the British Association, grade sizes had been pasted in the plates. The values were also available for fine sand and coarse sand only and had been interpolated for medium sand and extrapolated for coarse silt.

185. Dr Moyal under the able guidance of Professor White had verified the accuracy of Froude's experiments and the Author hoped that Mr Kumar working under Professor White would oblige the profession by verifying the accuracy of Table 3. From an analysis of all the available data, the Author felt that corrections necessary to the derived empirical formula would be very minor.

186. In §§ 113 and 114, Mr Lacey suggested the equation $\frac{V}{RS}=\frac{1760}{\sqrt{m}}$. In Table 26 two equations $\frac{1760}{\sqrt{m}}$ and $\frac{2525}{m^{0{\cdot}2}}$ had been compared for various silt diameters, and the percentage difference above or below had also been worked out, which showed that for *m* between 0·20 and 0·50, the percentage difference was less but it jumped up considerably when the diameter reduced below 0·10 mm.

TABLE 26

m	$\frac{1760}{\sqrt{m}}$	$\frac{2525}{m^{0{\cdot}2}}$	Per cent above or below
·04	8800	4807	+83
·05	7871	4597	71
·06	7185	4433	62
·07	6652	4298	55
·08	6228	4185	48
·09	5866	4088	43
·10	5565	4002	39
·15	4492	3691	22
·20	3935	3484	13
·25	3520	3332	5·6
·30	3213	3213	—
·35	2975	3116	− 4·5
·40	2783	3033	− 8·2
·45	2623	2963	−11·4
·50	2488	2900	−14·2

187. The Author thanked Mr Edgcombe for giving data about the weight of silt in suspension and the sand diameter on the bed of the Sukkur Right Bank Canals. In

Table 27 gradients had been worked out from Table 5 (p. 125) and also as suggested by Mr Brown in § 143. There was very little difference in the gradients worked out from the two methods and the original design gradients except for Rice Canal which had been designed at a steep gradient.

TABLE 27

Name of Canal	Silt in grammes/litre	Dia. of bed silt	f	Gradient 1 in — according to		Designed gradient 1 in —
				Table No. 5	Mr Brown	
N.W.C. RD 200	3·808	0·3048	0·54	15400	15700	14000
N.W.C. RD 8400	3·808	0·1880	0·59	14500	14900	
Rice RD 500	3·773	0·3822	0·51	18500	18200	12000
Rice 80000	3·773	0·1578	0·7	14900	14750	
Dadu RD 80000	3·902	0·2158	0·6	12900	13700	11500

188. The Author was grateful to Mr Brown for proposing a new formula for gradient. There was very little difference in gradient between Table 5 and those worked out from his formula as regards Sind conditions, but for Punjab conditions they were a bit steeper. As the formula was rational it was worth adopting. It could become of universal application by putting an average value of "m" for the locality in the form $S^{*}=\frac{0{\cdot}66m^{0\cdot2}f^{0\cdot66}}{Q^{0\cdot166}}$.

189. The Author was very grateful to Mr Kumar for his non-dimensional formulae and for testing the data from boundary layer theory.

190. The "m" referred to in the Paper was the weighted mean diameter of the silt particles. It would very nearly correspond to "m" = 80 of the grain size analysis curve.

191. As already stated in reply to Mr Ackers, the term laminar referred to the boundary layer portion only.

192. As stated in reply to Mr Lacey, Mr Kumar would do a service to the profession if he would verify the accuracy of the derived equations in Table 3 by working out Froude's friction on the lines of Mr Goodman from the known roughness of surfaces from experiments done in the Imperial College of Science and Technology under Prof. White.

NOTATION

ν = Kinematic viscosity
g = Acceleration due to gravity
ρ = Fluid specific gravity
ρ_S = Grain specific gravity
K = Roughness projections
$N = \frac{4RV}{v}$ = Reynolds number
δ = Thickness of boundary layer
τ_0 = Boundary shear stress
τ_C = Critical tractive force.

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