PAPER No. 192.

SILT-MOVEMENT AND DESIGN OF CHANNELS.

By Dr. N. K. Bose, Irrigation Research Institute.

In designing channels it has been long recognised that the silt that the channel will carry can have great influence in determining the ultimate section and slope to which the channel will settle down. This fact was most probably in the mind of Kutter and Ganguillet when they tried to modify the Chezy formula by introducing in the formula a variable factor 'n' which depends on the so-called rugosity of the channels. About 40 years ago Mr. Kennedy of the Punjab Irrigation introduced the idea of silt and turbulence explicitly into the subject and deduced his well-known relationship from about 20 sites on the Upper Bari Doab Canal system. More recently Mr. Lacey of the United Provinces Irrigation has again revived the subject and proposed in his two papers before the Institution of Civil Engineers, London, a number of relationships involving some of the usual hydraulic constants with a quantity known as the silt factor f.

For the last few years the Research Institute at Lahore has been busy with silt. It is known that the main difficulty that the previous investigations had in dealing with this problem was in defining silt. Kennedy in his siltometer proposed an instrument which but for some minor defects would have enabled him to classify silt successfully—some of these defects have been since removed by Dr. Puri and the modified siltometer is being used extensively in our field work. The siltometer that first solved the problem of classifying silt and made it possible to go ahead with the silt investigations has been perfected by Dr. Vaidhianathan and is being used constantly in the Research laboratory at Lahore. A Paper (No. 167) on this siltometer was read by its author before this Congress in 1933.

Collection of Data

For the last two years hydraulic data and bed-silt samples have been collected in the Research Institute from canal sites all over the Punjab which were known to be in regime. These data and the silt-samples are collected in certain sites daily and in others once a week. Up till now 14 sites have been analysed on the Lower Jhelum Canal, 10 sites on the Lower Chenab Canal, 4 on the Upper Chenab Canal, and 2 on the Upper Bari Doab Canal. From these sites, (*see* Table I), discharges (normal supply), section and water surface slope measured over a

distance of 500 feet upstream and downstream are obtained by a special man stationed at each site for this purpose. He also collects samples of bed-silts and suspended silt by special samplers. These data and silt samples are sent regularly to the Research Institute and each set of observations is entered in a standard form (Fig. I). These are permanent records giving the daily life history of each channel at these sites. Study of these life histories provides interesting and useful reading.

Suspended & Rolling Silt.

Silts in the channels have been broadly divided into two components—one is known as the rolling silt, a silt that hops and rolls and moves slowly as sand dunes on the bed of the canal. This silt is mainly confined to the bottom 3 to 6 inches of the canal. The other component is known as the floating silt—a silt that is always kept in suspension and once in suspension remains almost always in suspension. For the Punjab canals it is found that the line of demarcation can be roughly drawn somewhere near 0·05 mm. diameter—most of the bed-silts have diameter above this and most of the suspended silts below this—of course some finer silts are sometimes found in the first category and some stray coarser silts in the latter.

Up till now in our investigations we have mainly dealt with the quality of these samples, specially the bed-samples. Though it is well-known that the quantity of the silt also matters when present in large concentration, just as it sometimes happens in the Hwang-Ho and the Nile, it has been assumed that, with the concentration in which it is generally met with in the Punjab rivers, its effect will be negligible. It is proposed to investigate this effect later on.

Part I. Silt Movement.

Silt Size Distribution Curves.

These *bed-silt samples* are analysed by the siltometer and silt size distribution curves are plotted. These silt size distribution curves form a set of very valuable data. The recurrence of the same type or of different types of curves, month after month, shall determine whether the channel is keeping steady or altering its regime. This point will be made clear later in the text.

Distinctive Types of Distribution Curves and their significance.

These distribution curves of the bed silts can be broadly divided into three types, the Left Hand Type, the Middle Type and the Right Hand Type (*see* Fig. II). Type I, descriptively called the Left Hand Type, can be sub-divided into the Extreme Left Hand Type and Left

Hand Type. Type II is the Middle Type. Type III can again be subdivided into the Extreme Right Hand Type and the Right Hand Type. All these types are shewn in Fig. II. So altogether there are five types :

Extreme	Left Hand Type) Left Hand Type)	Type I.
	Middle Type ..	Type II.
Extreme	Right Hand Type) Right Hand Type)	Type III.

Of course these types cannot be put in absolutely cut and dried compartments. Very often they merge one into another. Just as the spectrum of a source of light runs from the ultra violet and through the visible part to the infra-red end, silt curves of canals also run through the above types if the silts are analysed all throughout the year (*see* Fig. III). Each of these types indicates a certain condition of equilibrium of a canal. So the annual frequency distribution of these types of curves for any canal is a very reliable indication of the stage of equilibrium of that canal. Now the first problem is to determine what is the significance of these types, to what stage in the development of a canal do they belong, and what indication do they give us of the stability of a canal. This problem can be attacked from two points of view ; either by conducting controlled experiments on channels that are known to be in a certain stage of development and then comparing the silt curves, or by studying the annual distribution of silt-curves of different canals and comparing them with the deductions from their hydraulic data. In the absence of the former, recourse to the latter method has been taken. The former method would have been preferable as it would have cleared out fundamental ideas and would have been free from certain assumptions that are inevitable in the latter method.

Take first of all the Middle Type. Before investigating its significance, it is interesting to compare the velocity distribution curves of flow of fluids in pipes under different conditions. The velocity distribution curve I (Fig. IV) in stream line flow in pipes is a parabola, whereas when turbulence sets in, this parabola flattens into curve II which shews a very sharp gradient at the walls and is almost flat over the remaining portion of the section. This can be easily explained from the fact that turbulence churns up the whole of the fluid and equalizes the velocities of water particles from one boundary layer to the other. Reynolds' famous experiments on the onset of turbulence shew also these churning effects. The Middle Type of the silt curves which are very much similar to Curve II in Fig IV, can therefore be associated with a stage in the canal flow when the churning action is going on

briskly and silts of all grade are made to move on the bed of the canal. This effect will only be apparent when there is some scouring going on the bed of the channel. So that the presence of this Middle Type is a sure indication that the channel is not silting.

The Left Hand Types indicate that the predominating components of the bed silts consist mostly of silts that are relatively fine and either the coarser components have already settled down in the upper reaches or are absent at the head. If the first, this type can indicate silting if it is not associated with the Middle Type. If the second, then this type will be mixed with the middle and the right hand types as well. If only the left hand type occurs and the equations (1) and (2) of Part II show that the silt is still coarse for the channel to carry, silting of the channel must follow.

The right hand type indicates that the predominating components of the bed silts consist mostly of particles that are relatively coarse and either the coarse compononts have been churned up from the bed or have come down to the section from some upstream point where scouring is taking place or from the head. In either of the latter alternatives, if the middle curves are absent, then the channels will have a strong tendency to silting.

It also appears that canals in which all the three types occur frequently with no bias for any particular type will be of the most stable type. In channels with big discharges, and consequently with a large range of fluctuations in the discharges, these three types will appear periodically. Type I will indicate that the channel has some fine silt that has settled down from suspension. Type II will indicate that the scouring action has started and has churned up silts of all sizes. Type III will indicate that the maximum velocity has been attained and all the five components have gone into suspension. Soon after there is an abatement of turbulence, fine silts that had gone into suspension will settle down and the curves will revert back to Type I, sometimes through an intermediate stage. In smaller channels with comparatively lesser discharge fluctuations all these variations might not occur. The peak of Type II curve will swing about its mean value but will not go beyond Type II.

The Extreme Left Hand Type occurs in certain channels where very fine silts are entering the head with consequent scouring and flattening of the curves into Left Hand Type.

The Extreme Right Hand Type is also frequent in canals that are getting very coarse silts from the upstream or from the head. This type can easily degenerate into the Right Hand Type which will shew that the channels are silting.

PART II.—DESIGN OF CHANNELS.

Bed-silt Sampling.

Since the publication of Mr. Lacey's first paper efforts have been made to give a physical explanation to his "f" the silt-factor. This has, however, been not possible (*see* Appendix I). As "f" holds the key to all his formulae excepting one, reference had had to be made to something else, something that would be directly connected with the silt that the channel is carrying. Now a channel carries silt in two different ways. One is what is called the floating silt which generally consists of particles below .05 mm., in diameter and the other is the rolling silt which is generally above this size. This rolling silt really forms the so-called boundary layer of Prandtl between the solid bed of the canal and its flowing fluid. The author has always been of opinion that the distribution of silt in this layer will really determine the energy distribution in the general body of the fluid and hence determine its section and slope. So the silt samples were taken from this bottom few inches, which contains the silt that moves in dunes, the silt that rolls and the silt that hops. The method of taking samples has been quite easy. Figs. V. and V*a* shew a silt sampler. This sampler is lowered with its catcher open into a channel at the place where it is intended to take the sample. When it is properly seated on the bed the handle is turned, a quantity of the dune on which the sample is resting is scooped in and the sampler is closed. It is then taken out of water and the silt thus trapped is put in a small gunny bag. The quantity required will just fill a cigarette tin. Table II will shew that consistent and representative bed samples have been obtained by this method. It also incidentally shews that the silt does not vary very much from day to day and from site to site within a few hundred feet of a site in the same channel.

Mean Diameter 'm' and Schocklitsch's Number K.

Having thus obtained a consistent and representative sample of the bed-silt the next problem was how to identify this silt. The size distribution curves were obtained by the siltometer devised by Dr. Vaidhianathan and the average particle size 'm' and a new characteristic known as the Schocklitsch's number K were worked out. The mean diameter 'm' is worked very easily. The centre of gravity of the area between the distribution curve as shewn in Fig. I and the corresponding Diameter axis is found in the usual way. The value of the diameter corresponding to this centre of gravity is really what is called 'm'. The number K is worked in the following way:—

From the distribution curve as shewn in Fig. I, a summation curve is plotted as in Fig. VI. The area included between the curve in Fig. I and the diameter-axis up to the ordinate passing through 0.1 mm., gives the total mass of all silt particles up to 0.1 mm., diameter in the

sample. This is plotted in Fig. IV as ordinate corresponding to 0.1 mm. diameter. Similar areas are worked out for ordinates passing through .2, .3, .4, .5, .6 mm. diameters and plotted in Fig. VI. As most of the silt met with in the Punjab have diameters smaller than 0.6 mm., an ordinate through 0.6 mm. diameter is drawn in Fig. VI and a line parallel to the diameter-axis is drawn through the 100 per cent. point on the % by weight axis. Then the two areas above and below the mass curve are denoted by A and B and K in this case is denoted by :—

$$K=\frac{A}{B}.$$

This K is what is known as the Schocklitsch's Number. It will be seen that K is a non-dimensional quantity and as the quantity of coarser silt in the sample increases the area B diminishes and the value of K increases. So that the coarser the silt sample the higher the value of K. As in all our investigations we have been dealing with silts below .6 mm. diameter we shall simply call the Schocklitsch Number corresponding to this by K and connect this number for silts with that for any higher maximum range x by :—

$$K_x^s=K.\ \frac{1}{\frac{x}{.6}\ (1+K)-K}$$

This number 'K' has this advantage over 'm' that whereas 'm' gives us only an idea about the average value of the size of the particles met with in the samples, it does not indicate which side of the sample predominates, the finer or the coarser, unless also the two limits and the peak of the curve in Fig. I are known. The two areas A and B in K really indicate the quantity of coarser and finer particles in the sample and as K increases it is a sure indication that the coarser element is gaining over the finer element.

Having thus decided in favour of K we had first of all to sift our data, which consisted of figures of discharges, section, slope obtained in some cases daily, in some cases weekly from sites spread over few canal systems of the Punjab. Some of the data was evidently unsuitable, as the fluctuations in discharges were found to be considerable and the channels could not be considered as running steady. The remaining data was averaged out for each site by months, for some sites we had about 24 averages, for others less. These monthly averages of hydraulic data and the value of K shows slight variations from month to month, but it has been found that for steady sites the variations are never great from the total mean. Only for a couple of channels it has been found that the deviations from the total mean had been increasing, indicating definitely that the channel was going off regime (*see* Appendix II). These sites (*see* Table IV) were eliminated from the other set of data, but

they were kept under observation, as they were expected to provide valuable check to the validity of the rules derived from other regime sites.

Method of Design of Channels

The analysis first started on the assumption that the relationships that were to be deduced from these sets of data should be of immediate practical application. An Engineer's first concern when he is going to design a channel was to know what slope to give to his channel if it was to carry a certain discharge and a certain silt. Statistical analysis (*see* Appendix II) of the data as set forth in Table IV, with this definite requirement of the engineers always before the mind, lead to the following relationship between S, K and Q :—

$$S \times 10^3 = \frac{K^{\frac{1}{2}}}{Q^{\frac{1}{4}}} \qquad (1)$$

where S is the water surface slope measured in feet per thousand feet, K the Schocklitsch's Number for the silt that the channel can carry and Q the total discharge in cusecs.

This relationship has a very high correlation—about 90 per cent.—which is a very close approach to a law of nature, inspite of the fact that silt can and does vary considerably from month to month.

Having determined the slope, the next problem is to determine the shape of the channel, which means whether the channel is broad and shallow, or narrow and deep. This conception can be mathematically expressed by the ratio between the depth and the width of a channel or, what is better from the hydraulic standpoint, by the ratio between the hydraulic mean radius R and the wetted perimeter, P, so that shape can be expressed by $\lambda = \frac{R}{P}$.

It has been found from field observations as well as from laboratory experiments that the shape of a channel is very closely related to its slope and silt. Prof. Gibson notes in his Report about the model experiments on the Severn River: " It may be of interest to note that a distortion of scale is usual in nature, small streams flowing through alluvial ground having much steeper side slope and gradient than larger rivers of similar regime in similar ground. In a very large river such as the Mississippi, the Ganges, or the Irawadi, the maximum depth will rarely exceed 1 : 100 of the maximum width while in a small stream in similar ground the ratio will seldom be less than 1 : 5."

This led the way to investigate a relationship between λ, K and S and it is found that the relationship is equally significant as that between Q, K and S in equation (1). This relationship is :—

$$\lambda = \frac{R}{P} = \frac{S^{\frac{1}{3}}}{K^{\frac{1}{2}}} \qquad (2)$$

The shape of channel is admittedly an indication as to whether it is in good or bad regime. But this by itself is not enough to solve the whole problem of design. This relation together with the only relation of Lacey not involving his "f", the silt-factor, *viz.*,

$$P = 2.668\ Q^{\frac{1}{2}}.$$

will solve the whole problem of design.

These three relationships, which are reproduced below, furnish all the information that could be required for the design of a channel, if the discharge and the silt that it is going to convey are known :—

$$S \times 10^3 = \frac{K^{\frac{1}{2}}}{Q^{\frac{1}{4}}} \qquad (1)$$

$$\lambda = \frac{R}{P} = \frac{S^{\frac{1}{3}}}{K^{\frac{1}{2}}} \qquad (2)$$

$$P = 2.668\ Q^{\frac{1}{2}} \qquad (3)$$

Nomograms and diagrams are provided for the first two relationships.

These relationships are frankly empirical and have not got the sanctity of the laws of nature. However, they have been derived from *a* collection of regime data (*see* Table IV) and the high correlations that are found to exist between them justify their adoption. These relationships are put before the engineers so that they may be tested and modified if necessary. The only quantity which an engineer will find difficult to fix is K. It has been found that there is an annual variation in the values of K of any particular channel. These variations are generally found to be about 25 per cent of the mean value, but no seasonal trend is found to exist (*see* Fig. VII). This fact might be contested by engineers who generally find very fine silt coming down in the summer months and rather coarse silt in winter. It is necessary therefore to emphasise the fact that K refers to the bed silt that rolls and hops and moves in dunes and not the floating silt. For redesigning or remodelling a channel it is not very difficult to fix the average value of K, so that the required slope can be easily determined. If it is found that the channel cannot be given any slope near enough to the required slope, the only other alternative will be to exclude silt at the head.

To design a system of new channels where nothing is known as to the silt that is likely to come to the canals from the river, the problem is much more difficult. Enough data are not available to shew how K varies from the head regulator of any canal system to the tail end of its Main Line. This is a problem which must be solved first before the above relationships could be of practical use to the project engineer.

It must be distinctly understood that the above relationships are meant as guides to design. Though the solutions that are obtained from

them are unique mathematically yet in practice one finds a certain amount of latitude which depends on disturbing factors that cannot be mathematically accounted for. In using these formulae for the purpose of design one has got to remember the following facts :—

(1) That the head regulator of a distributary might not be taking the same quality and quantity of silt as is running in the parent channel.

(2) That there is a considerable seasonal variation in the silt of the parent channel.

(3) That the off-takes in the distributaries might be silt-selective outlets and drawing more—and sometimes less—than its proper share of the silt.

(4) That the channel is laid in such a terrain that the outlets are serving very high lands and as such cannot draw much silt. Such a case is met with in the two channels at the tail of Southern Branch (Lower Jhelum Canal)—Kirana and Lalian Distributaries. Kirana taking off at an angle has to draw more and coarser silt; at the same time the terrain it serves is very high so that the outlets don't draw their proper share of silts. Whereas Lalian, taking off straight and therefore finer and smaller quantity of silt as well, has to serve comparatively low lands an as such its outlets draw their proper share. There is no silting in t Lalian, whereas Kirana has been silting and cutting its berm. The two channels appeared on analysis to be anomalous, till the abo explanation of their behaviour was furnished by Mr. Bedford.

If one takes account of these disturbing factors, formulas (1 and (3) will give values very close to the slope and the shape at the channel will run properly. These disturbing factors it ma possible to eliminate if rigid control is exercised over the silt entry a head of a canal and its various off-takes on the way. It shoul possible to know the exact silt exclusive values of various types of takes. This would involve a systematic study of the whole canal syst from head to tail and the examination of a few old channels is of no us This work is being started now in the Research Institute.

It will be seen that, given the silt and the discharge, the equation (1) determines the *slope* of the channel, the equation (2) the *shape* and the equation (3) the *scale*. It is quite natural that the slope and the shape of a channel should be determined by the silt it carries. It is well-known that the fineness of the silt generally decides whether a channel is to have a steep or a flat slope, *i. e.*, a narrow but deep section or a broad but shallow one. The third relation that involves only discharge determines its scale.

Summary

It has been possible to obtain the following results from the above analysis:—

(1). That the annual frequency distribution of the types of size distribution curves for the bed-silts of any canal is a very reliable indication of the stage of equlibrium of that canal.

(2). That silt plays a very important part in controlling the regime of a channel and the Schocklitsch's Number K that has been chosen to represent it is a real characteristic of silt.

(3). That with the three equations (1), (2), and (3), it is possible to design a canal system or to remodel any distributary, knowing only the discharge and the silt that the system will carry. These equations will serve as guide to design engineers.

In conclusion I would like to acknowledge my indebtedness to Dr. E. McKenzie Taylor, Director of the Punjab Irrigation Research Institute, for giving me all the facilities for carrying out this work and to Dr. Vaidhianathan and Mr. Chanan Singh, of the Institute, who have done all the silt analyses that are mentioned in this paper.

APPENDIX I.

MR. LACEY'S SILT-FACTOR "f" AND BED SILTS OF CANALS.

Mr. Lacey in his papers mentioned before had tried to connect his silt-factor "f" with the average diameter of the bed silt that the channel carried. He has as a matter of fact derived a relationship between the two in both his papers.

$$f=8\sqrt{d} \qquad (1)$$

where 'd' has been expressed by Mr. Lacey as "the average diameter of the materials forming the bed at any given moment, that is the average diameter of the incoherent alluvium forming the active boundary."

In the Research Institute at Lahore a number of bed-silt samples and hydraulic data of the corresponding section of the canals were obtained from sites that were considered to be in regime by the local Executive Engineers. These sites include some of the research sites selected afterwards specially for these investigations. The values of "f" have been worked out from two of Mr. Lacey's relationships:—

$$V=1.1512\sqrt{f_1\ R} \qquad (2)$$

$$f_2^{\frac{3}{2}}=\frac{10^6}{370.68}R^{\frac{1}{2}}.\ S \qquad (3)$$

These two values of "f" are tabulated in the accompanying Table III together with the values of the average diameters of the bed-silts. These figures speak for themselves.

APPENDIX II.

STATISTICAL ANALYSIS.

This analysis has been carried out on the set of data given in Table IV. Table IV contains lesser number of sites than that given in Table I—the reason why inspite of this Table IV has been selected for analysis in preference to Table I will be made clear later on. What this analysis really means and what it does not mean will be explained first.

This mass of hydraulic data and silt samples were collected from sites known to be in regime with the following points in view:—

1. First and foremost, to find, if possible, a representative characteristic of silt, a characteristic that will define silt, both from its physical and hydraulic standpoint. Two such single-valued characteristics were available in m and k. It has been shewn before that k is superior to m from physical consideration, and from hydraulic consideration it also appears that k is superior to m and is a real hydraulic constant whose introduction in the analysis really improves the correlation. In the relation (2) the correlation coefficient between λ and s is 61 per cent. but the correlation coefficient between λ, k and s is 89 per cent., an improvement which points to the distinct association of k with λ and s. Similar improvement is noticeable in the relation (1) by associating k with q and s.

2. Certain relevant hydraulic constants were chosen and their variations were studied from day to day—in some cases over a period of 24 months. Some of these variations were found to be increasing with time—in some channels these increases were noticeable after 10 or 12 months had elapsed; in others they started from the very beginning. In the first case, data for these 10 or 12 months have been averaged out and put down in Table IV and in others where the channels are slowly going off regime but their rate of drift is small but perceptible after the lapse of some considerable time, average values for these channels have also been worked out and put in Table I. Only a few channels have been definitelty rejected.

Channels in Table IV have been assumed to be in regime for the period under consideration. In almost in all cases enquiry has shewn that the channels were tampered with in this period and they have started going off. A very good case in point is the Chiniot Distributary. This distributary was fitted with silt-skimmers sometimes in January 1934 and the effect of the finer silt had made itself felt in the scour which took about 6 to 7 months to reach our place of observation. Another similar site is Main Line Lower (Lower Chenab Canal) at Sagar. This site was a perfectly good site till coarser silts that were scoured down from the head reaches arrived and is gradually upsetting the regime.

Correlation coefficients are generally used for two purposes :—

1. As an evidence of *causation.*
2. As an evidence of *association.*

In its first rôle it is rather a dangerous weapon to handle. When investigating causation it is usually better to decide first on other grounds that a causal relationship is likely, and then to conduct a close analysis of other possible factors before using the correlation coefficient as evidence.

If a linear regression formula is used to predict one character from another, the correlation coefficient may safely be used to define the accuracy of the prediction.

It was therefore decided to use correlation in its latter rôle and as the major problem was to get a regression between s, k, and q, also between λ, s and k, analysis was confined to this part. Correlation coefficient was used only to see the degree of association and goodness of fit.

The regression equations as given in the text are :—

$$S \times 10^3 = \frac{K^{\frac{1}{2}}}{Q^{\frac{1}{4}}} \qquad (1)$$

$$\lambda = \frac{R}{P} = \frac{S}{K^{\frac{1}{2}}} \qquad (2)$$

The degree of association is given by the correlation coefficient .90 and the closeness of fit is given in cols. X and XI in Table IV. The regression equations as derived from Table I show slight departure from these equations (1) and (2) and the correlation coefficient 0.82 also shews a slight falling off in the association.

It must be clearly understood that these relationships (1), (2) and (3) are definitely empirical and as such cannot stand the usual operations of mathematics, such as elimination, differentiation and other similar operations that can be safely performed on relationships derived from strict theoretical considerations only. Lack of appreciation of this draw-back of empirical relationships has led very often to unnecessary complication.

TABLE I.

No.	Description & R. D.	Period.	Q.	S×10³.	R.	P.	K.	V.	f_1.	f_2
		Lower Chenab Canal Circle.								
1	Main Line Lower, R. D. 149000 ..	October 1933 to August 1935 ..	4424.30	.19	7.58	201.82	2.115	2.89	.830	1.258
2	Jhang Branch, 221000 ..	September 1933 to July 1935 ..	2049.08	.19	6.09	128.80	1.183	2.61	.842	1.170
3	Khai Distributary, 4943 ..	October 1935 to October 1934 ..	40.03	.29	1.58	16.87	.576	1.51	1.088	.988
4	Sarangwala Distributary 6300 ..	October 1933 to July 1935 ..	59.34	.28	1.61	24.28	.834	1.51	1.067	.972
5	Hafizabad Distributary 3050 ..	November 1933 to August 1935 ..	23.11	.34	1.33	11.84	.686	1.43	1.159	1.038
6	Nasrana Distributary, 3275 ..	September 1933 to October 1934 ..	273.03	.164	3.00	39.94	.767	2.28	1.206	.837
7	Rakh Branch, 7260 ..	November 1934 to August 1935 ..	1058.82	.18	4.58	90.20	2.120	2.53	1.053	1.026
8	Jhang Branch, 7260 ..	December 1934 to August 1935 ..	2816.28	.20	6.93	143.98	2.116	2.83	.871	1.264
9	Mian Ali Branch, 2850 ..	November 1934 to August1935 ..	557.75	.20	3.62	64.27	1.242	2.41	1.209	1.018
10	Main Line, 181000 ..	March 1935 to August 1935 ..	4445.96	.18	7.39	207.39	2.077	2.90	.858	1.203
11	Lagar Distributary, 2500 ..	November 1934 to August 1935 ..	30.20	.23	1.46	17.82	.485	1.15	.683	.825
12	Chiniot Distributary, 2900 ..	October 1933 to July 1935 ..	163.13	.24	2.37	36.64	1.022	1.88	1.124	.997
13	Gugiana Distributary, 3200 ..	September 1933 to July 1935 ..	28.47	.30	1.29	16.20	.540	1.36	1.081	.945
14	Jamal Jatti Distributary, 2300 ..	September 1933 to October 1934 ..	26.82	.326	1.28	16.03	.570	1.29	.980	.997
		Lower Jhelum Canal Circle.								
15	Southern Branch, 102,500 ..	September 1933 to November, 1934 ..	784.51	.145	4.45	81.58	.854	2.14	.776	.880
16	Kirana Distributary, 2675 ..	October 1933 to November 1934 ..	439.25	.201	3.41	60.26	.910	2.12	.993	1.001
17	Lalian Distributary, 1700 ..	October 1933 to November, 1934 ..	357.90	.158	3.77	44.81	.894	2.11	.890	.832
18	Northern Branch, Lower 73500 ..	March 1935 to August 1935 ..	1380.995	.17	5.48	100.34	1.382	2.49	.853	1.049
19	Fatehpur Distributary, 10200 ..	February 1935 to August 1935 ..	44.45	.22	1.80	16.80	.601	1.44	.868	.859
20	Mithalak Distributary, 4000 ..	March 1935 to August 1935 ..	131.01	.19	2.82	25.25	.750	1.83	.895	.905
21	Northern Branch, U/S Ludewala 163000..	September 1933 to August 1935 ..	1180.14	.134	5.23	90.89	1.098	2.49	.893	.881
22	Northern Branch, D/S Ludewala 170289..	September 1933 to August 1935 ..	768.98	.16	4.47	74.20	.996	2.28	.876	.941
23	Sulki Branch, 2300 ..	September 1933 to August 1935 ..	347.16	.20	2.88	56.09	.961	2.13	1.187	.943
24	Bhek Distributary, 1500 ..	September 1933 to August 1935 ..	55.43	.28	1.73	20.60	.719	1.55	1.047	.996
		Upper Bari Doab Canal Circle.								
25	Aliwal Distributary, 1500 ..	May 1934 to February 1935 ..	81.95	.30	1.80	26.60	1.484	1.77	1.312	1.057
26	Majitha Distributary 4400 ..	February 1934 to January 1935 ..	83.63	.25	2.17	22.79	1.075	1.66	.957	.996

$$f_1 = \left(\frac{V}{1{\cdot}1512\ R^{\frac{1}{2}}}\right)^2$$

TABLE II. K.-VALUES.

No.	Samples from the *same tin.*	Samples taken within the *same hour.*	Samples taken within the *same day.*	Samples taken within the *same week.*	Samples taken from different points at the *same time.*	Effect of temperature on the *same sample.*	REMARKS.
1	.609	.473	.676	.662	.572	.586 (17° C.)	
2	.593	.513	.647	.671	.479 (10′ U/S)	.603 (20° C).	These samples were taken from the Buciana Distributary R. D. 7,400 Lower Chenab Canal.
3	.633	.546	.620	.644	.566 (20′ U/S).	.631 (23° C).	
4	.590	.599	.612	.584	.519 (10′ D/S).	.662 (26° C).	
5	.592	.542	.520	.654	.630 (80′ D/S).	.681 (29° C).	
6	.606	.603	.588	.592	.567 (30′ D/S).	.724 (32° C.)	
Mean	.599	.546	.627	.636	.556	.648	
Standard Deviatio	.0078	.047	.027	.034	.047		

Total Mean .593

It will be seen that the individual values in each column differ only slightly from the mean value of each column, also from the total mean .593. The first column has been put in to shew how reliable are the data worked out by the siltometer. This column refers to six samples taken from the same tin and analysed one after another—the close agreement testifies to the accuracy of the siltometer. In the last column the effect of temperature on the apparent diameter size of the particles is illustrated.

TABLE III.

No.	Description of the Site.	$m \times 10^2$ in mm.	V/t/Sc.	R.	$S \times 10^4$.	f_1.	f_2.
1	Mianwali Distributary (U. J. C.) ..	21.36	1.60	3'.03	1.00	.638	.604
2	Muridke Distributary (U. C.C.) ..	12.94	1.61	2.22	2.41	.881	.979
3	Jahania Distributary (L. B. D. C.) ..	13.50	1.75	5'.34	1.00	.433	.730
4	Assan Distributary (W. J. C.) ..	15.20	1.34	1'.51	2.40	.897	.859
5	Lakhuana Distributary (L. C. C.) ..	16.30	1.48	1'.06	3.80	1.559	1.037
6	Dijkot Distributary (L. C. C.) ..	16.00	1.32	0'.86	3.00	1.529	.826
7	Sher Shah (Chenab) ..	19.60	1.68	2'.50	2.00	.852	.900
8	Bhatinda Branch (S. C. C.) ..	20.60	2.05	4'.32	2.50	.734	1.253
9	Dulwan Distributary (L. B. D. C.) R. D. 500.	15.60	1.76	4'.03	1.00	.580	.664
10	Main Line (L. B. D. C.) R. D. 543000 ..	15.70	2.10	5'.63	1.00	.591	.743
11	Jasrana (W. J. C.) ..	20.50	1.70	1'.88	2.40	1.160	.924
12	Fultna Minor (W. J. C.) ..	12.90	1.25	1'.48	3.70	.797	1.138
13	Kasur Branch (U. B. D. C.) ..	18.26	1.84	2'.17	2.40	1.177	.967
14	Teona Distributary ( ). ..	24.94	1.91	2'.16	2.40	1.274	.967
15	Chiniot Distributary (L. C. C.) ..	11.66	1.53	1'.10	2.20	1.606	.729
16	Chillianwali Distributary (U. J. C.) ..	29.94	1.33	1'.10	2.80	1.213	.856
17	Gugiana Distributary (L. C. C.) ..	17.64	1.39	1'.33	2.70	1.096	.890
18	Jhang Branch (L. C. C.) ..	27.08	2.66	6.18	1.60	.864	1.048
19	Sarangwala Distributary (L. C. C.) ..	35.74	1.77	1'.90	2.40	1.244	.927
20	Bhek Distributary(L. J. C.) ..	18.62	1.58	1'.78	2.40	1.058	.907
21	Khai Distributary (L. J. C.) ..	19.28	1.55	1'.62	.60	1.119	.752
22	Khanuana Distributary ( ) ..	18.20	1.55	3'.22	1.60	.563	.843

TABLE IV.

No.	Description & R. D.	Period.	I. Q cu/sec.	II. S×10³.	III. K.	IV. R/P.	V. R.	VI. P.	VII. $\sqrt{f}$/sec.	VIII. f_1.	IX. f_2.	X. S×10³.	XI. R/P.	XII. P Lacey.	XIII. S×10³ Lacey.
						Lower Chenab Canal Circle.									
1	Main Line Lower, 149000 ..	October 1933 to July 1934 ..	4417.76	.20	1.856	.0373	7′.51	201′.63	2.81	.792	1.298	.167	.0435	177.3	.3016
2	Jhang Branch, 221000 ..	September 1933 to July 1935 ..	2049.08	.19	1.183	.0473	6′.09	128′.80	2.61	.843	1.170	.162	.0533	121.8	.3676
3	Khai Distributary 4943 ..	October 1933 to October 1934 ..	40.03	.29	.576	.0935	1′.58	16′.87	1.50	1.073	.989	.302	.0879	16.88	.3278
4	Sarangwala Distributary, 6300 ..	October 1933 to January 1935 ..	59.71	.29	.854	.0672	1′.62	24′.2	1.52	1.068	.999	.332	.0722	20.62	.3205
5	Hafizabad Distributary, 3050 ..	November 1933 to September 1934 ..	20.48	.32	.607	.1079	1′.26	11′.68	1.38	1.139	.979	.366	.0885	12.17	.4014
6	Nasrana Distributary 3275 ..	September 1933 to July 1934 ..	273.77	.17	.735	.0756	3′.02	39′.92	2.27	1.286	.860	.211	.0651	44.15	.3110
7	Lagar Distributary, 2500 ..	November 1934 to August 1935 ..	30.20	.23	.485	.0823	1′.46	17′.82	1.16	.695	.825	.297	.0887	14.66	.5615
8	Chiniot Distributary, 2000 ..	October, 1933 to July 1934 ..	166.29	.28	1.053	.0621	2′.18	23′.74	1.98	1.296	1.092	.286	.0612	34.41	.3621
9	Gugiana Distributary 3200 ..	July 1934 to July 1935 ..	29.01	.30	.606	.0803	1′.31	16′.26	1.36	1.064	.950	.335	.0867	14.37	.3554
10	Jamaljatti, 2300 ..	January 1934 to October 1934 ..	28.07	.33	.614	.0801	1′.31	16′.31	1.32	1.002	1.013	.340	.0889	14.24	.3259
						Lower Jhelum Canal Circal.									
11	Southern Branch, 102500 ..	September 1933 to November 1934 ..	784.51	.145	.854	.0545	4′.45	81′.58	2.15	.783	.880	.175	.0573	74.73	.3848
12	Kirana Distributary, 2675 ..	October 1933 to November, 1934 ..	439.25	.201	.910	.0566	3′.41	60′.26	2.11	.084	1.001	.208	.0619	55.92	.6194
13	N. B. U/S Ludewala 163000 ..	September 1933 to August 1935 ..	1180.14	.134	1.098	.0376	5′.23	90′.89	2.48	.886	.881	.179	.0492	91.66	.4276
14	N. B. D/S Ludewala 170285 ..	September 1933 to August 1935 ..	768.98	.16	.996	.0602	4′.47	74′.20	2.32	.907	.941	.190	.0548	73.99	.4792
15	Sulki Branch, 2300 ..	October 1933 to August 1935 ..	347.16	.20	.961	.0514	2′.88	56′.09	2.14	1.198	.943	.227	.0601	49.71	.2865
16	Bhek Distributary, 1500 ..	September 1933 to August, 1935 ..	55.43	.28	.719	.0841	1′.75	20′.80	1.55	1.046	.993	.311	.0778	19.86	.3017
						Upper Bari Doab Canal Circle.									
17	Aliwal Distributary, 1500 ..	May 1934 to January 1935 ..	81.95	.30	1.484	.0678	1′.80	26′.60	1.71	1.224	1.056	.405	.0554	24.15	.3742

(1). In column VIII and IX, f_1 and f_2 have been calculated from the two relations of Mr. Lacey as quoted in Appendix I.

(2) In column X and XI values have been calculated from the relationships (1) and (2) derived in Appendix II—they have been worked out to see the goodness of fit of the Regression Equations (1) and (2).

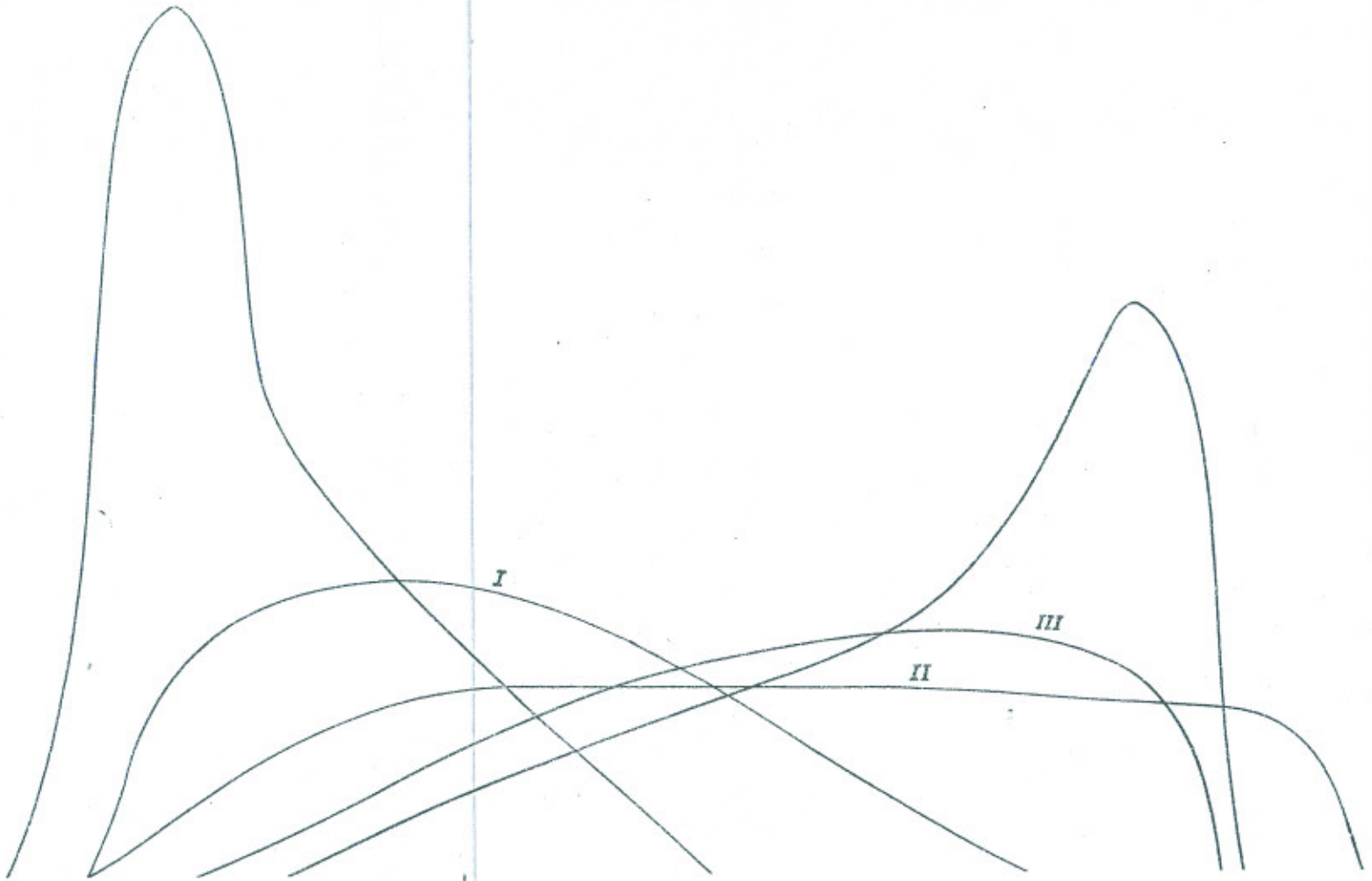
(3) In Column XII, P Lacey has been calculated from the relationship $P=2.668\ Q_{\frac{1}{2}}$ quoted in the text as relation (3).

(4) In column XIII, Sx10³ (Lacey) has been calculated from the second relationship of Lacey quoted in Appendix I.

$$Sx10^3 = \frac{370.68}{10^3 . R^{\frac{1}{2}}} . f^{3/2}$$ in which f_1 in column VIII has been used.

SIZE DISTRIBUTION CURVES.

FIG. II
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SIZE DISTRIBUTION CURVE

FIG.1
192

REG.NO:- 372-C/35.

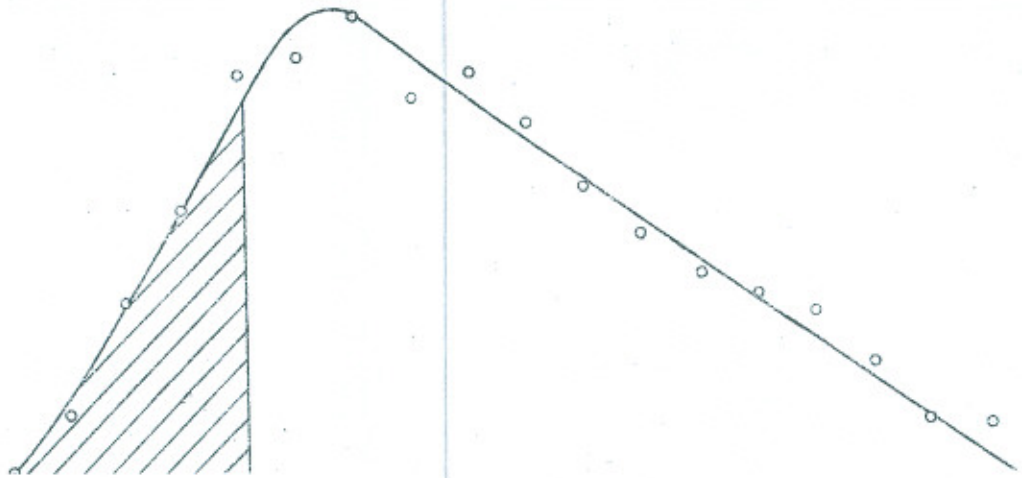
CANAL:- L.J.C. BRANCH:- N.B. D/S LUDEWALLA.

DISTY:- R.D. :- 175,000

DATE :- 25.9.35.

Q	A	$S \times 10^3$	R	D	P	B	V
731·99	317·81	·16	4·29	4·87	79·06	60·52	2·30

m	σ	k
·28 mm	·086	·870



SIZE DISTRIBUTION CURVES OF THE JHANG BRANCH (L.C.C.) R.D. 221000.

FIG. III
192

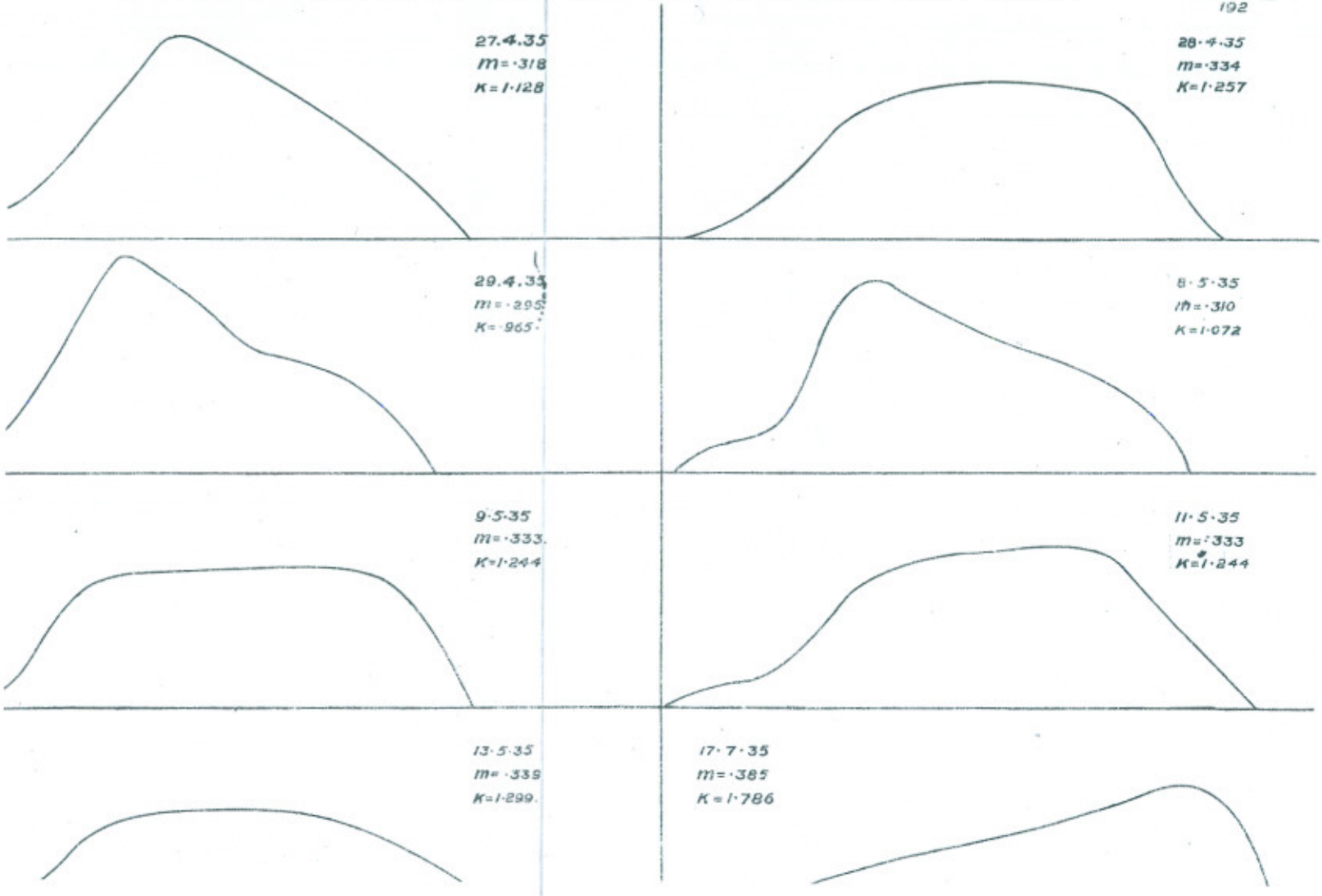
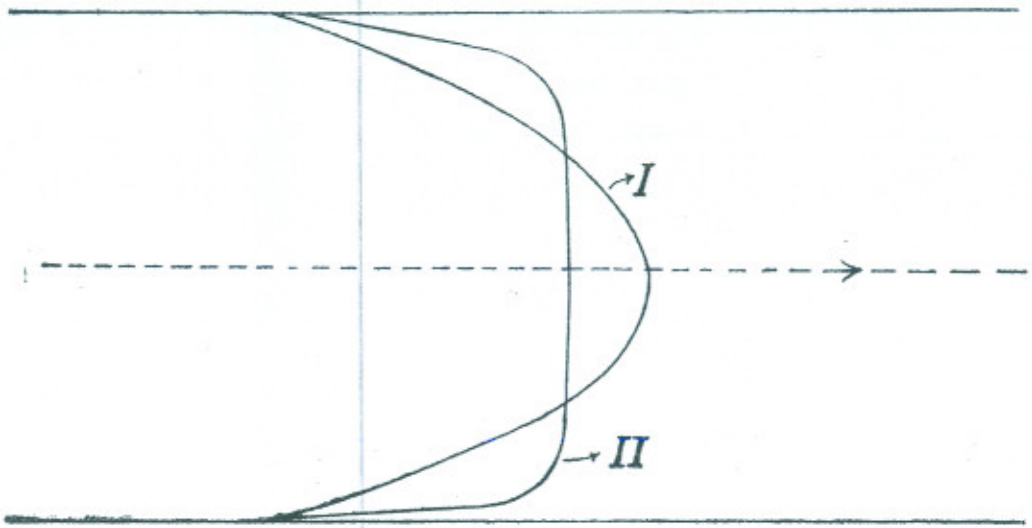


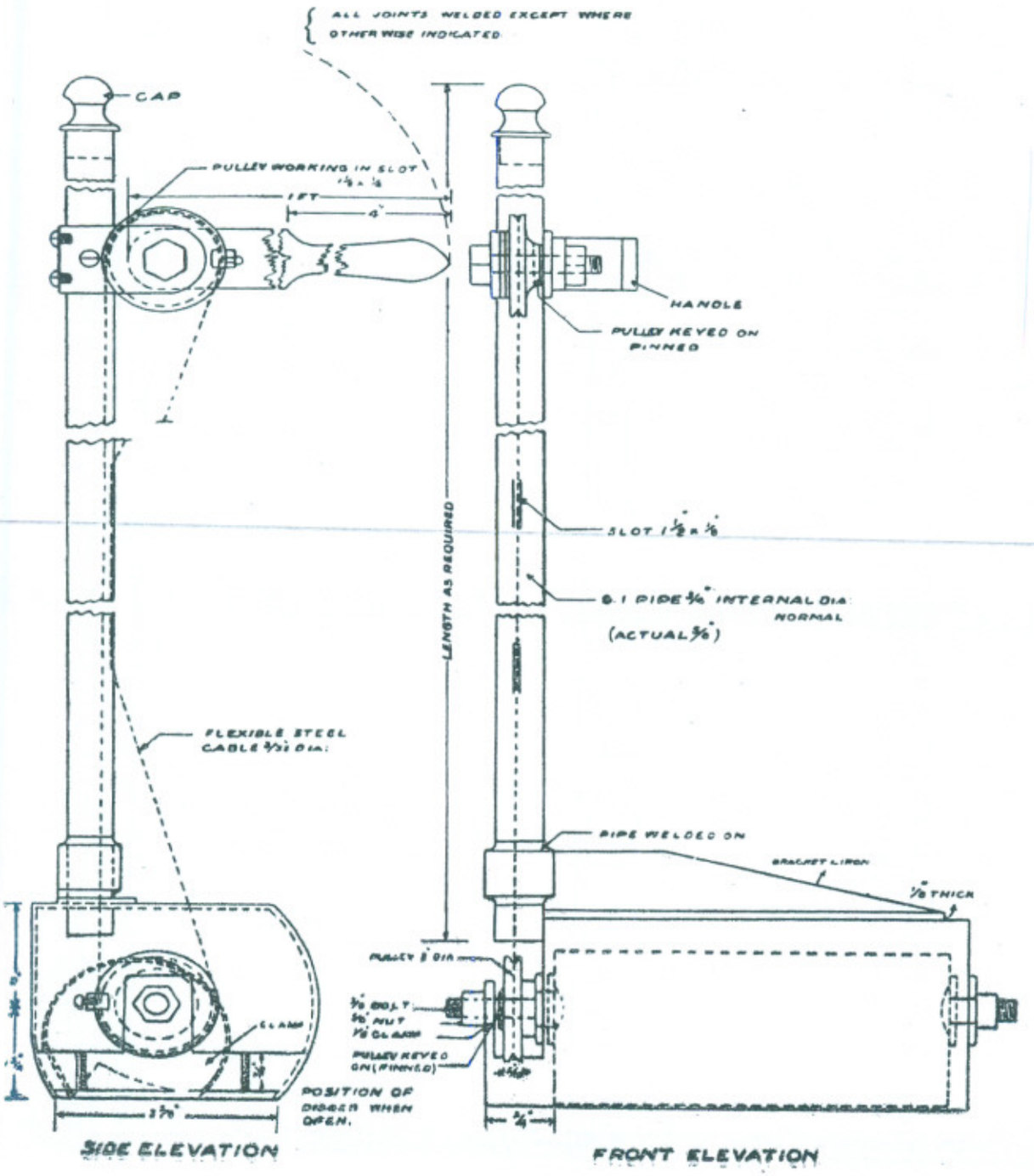
FIG. IV

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LATEST TYPE OF BED SILT SAMPLER

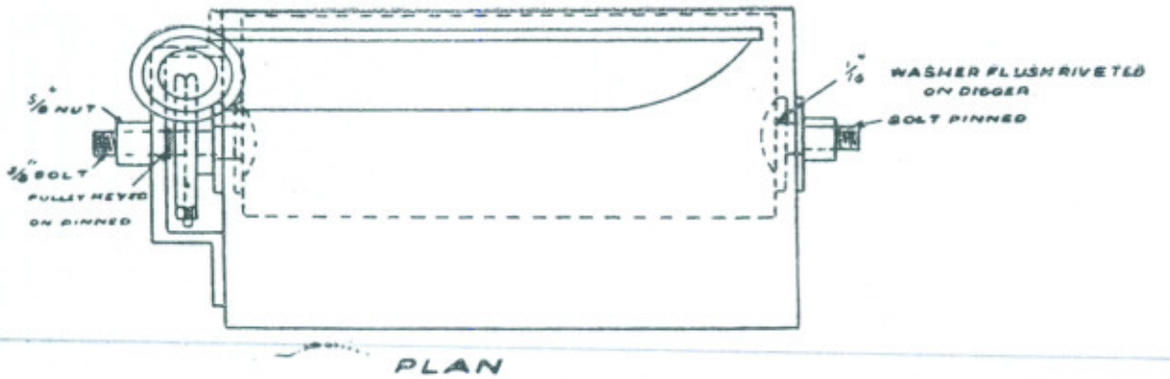
FIG. V
198



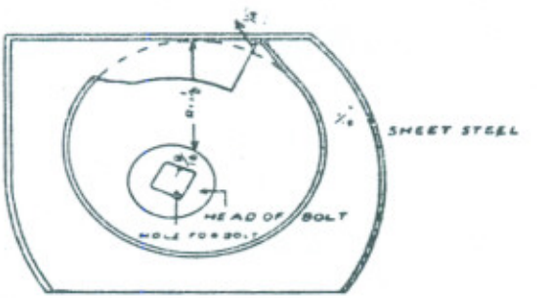
LATEST TYPE
OF
BED SILT SAMPLER

FIG. XA
192

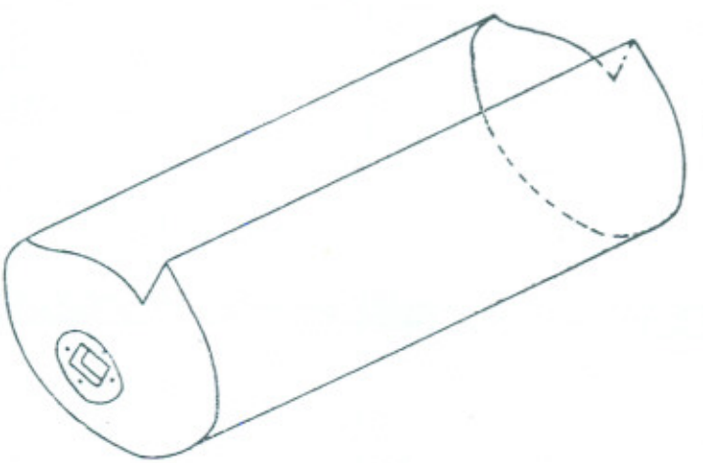
ALL JOINTS WELDED EXCEPT WHERE OTHERWISE INDICATED.



PLAN



SECTION WITH DIGGER CLOSED.



ISOMETRIC VIEW OF THE DIGGER

SUMMATION CURVE

FIG.VI
192

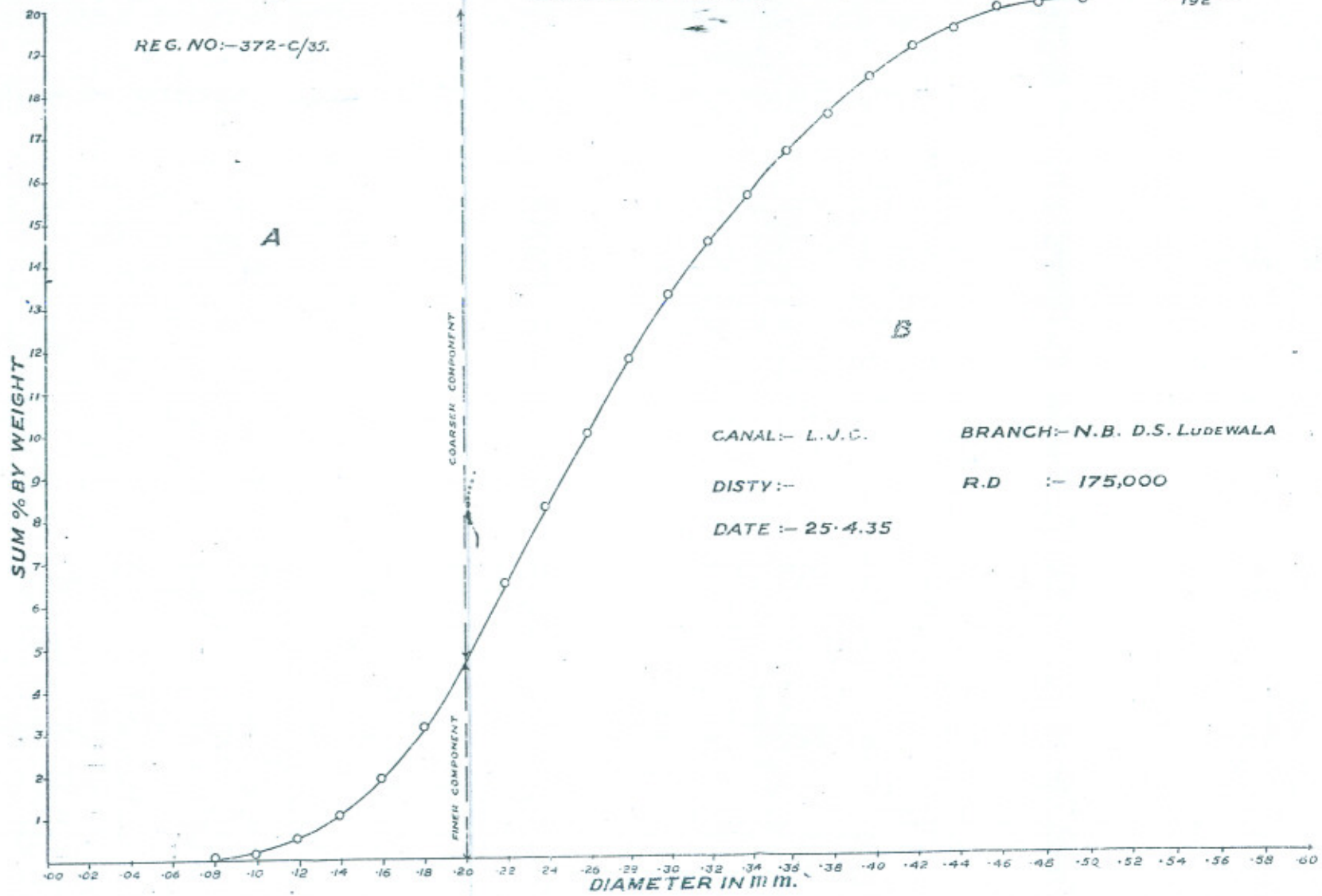
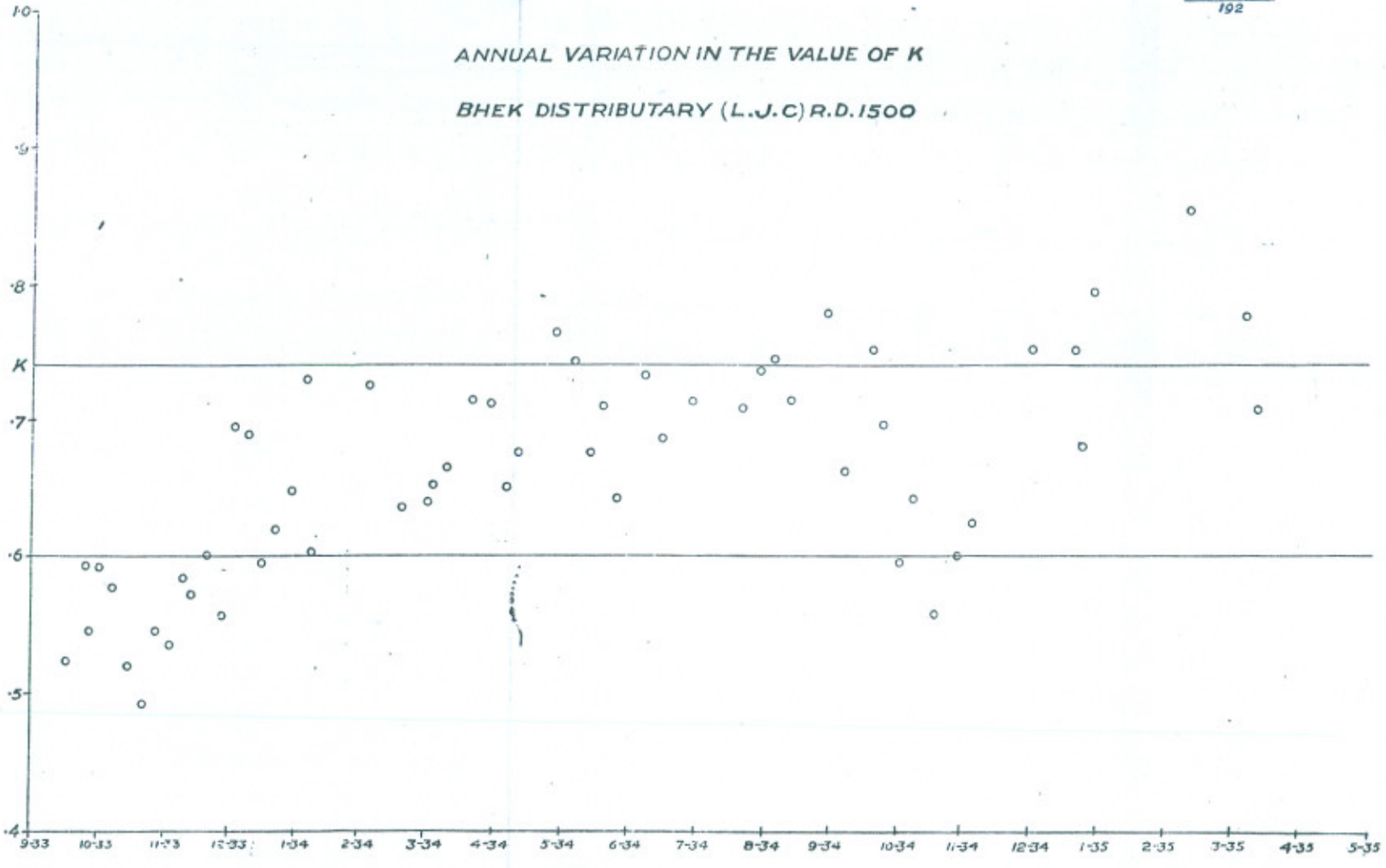


FIG. VII
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ANNUAL VARIATION IN THE VALUE OF K

BHEK DISTRIBUTARY (L.J.C) R.D. 1500



DISCUSSION.

In introducing his paper DR. **N. K. Bose** explained the aim and the scope of the paper. It was well known that the problem of determining the regime of flow of water in artificial channels was a very complicated one. Attempts had been previously made to attack this problem from the purely theoretical stand-point. These attempts had mostly failed due to the fact that a simple streamline theory of flow of water was not capable of dealing with the complexities of natural movement of water in canals. Of the recent attempts at empirical solutions, those of Kennedy and Lacey were worth mentioning.

His paper was an attempt on the latter line with this difference that while Kennedy omitted silt altogether from his relations and Lacey had tried to bring this into the picture in a form which varied with the occasion, the author's idea was to bring in silt as a physical and hydraulic entity. This has been achieved by introducing a quantity K which was a function of the mean diameter of the silt-sample. This number had been used by Prof. Schocklitsch of Brunn in some of his model experiments on silting and scouring; but this was, the author claimed, the first occasion when it was being used as defining the dynamical behaviour of the silt that rolls, the silt that hops and the silt that moves as dunes on the bed of canals. It must be definitely understood that K did not represent the full dynamical effect of rolling silt. To do this, account had to be taken of the quantity of silt and the temperature of the silt laden water. It was hoped to extend the silt observations on these lines in future.

An objection might be raised against the use of K. As it was a function of the mean diameter 'm', 'm' might have been used as well; but as K was slightly superior to 'm' from the physical point of view and gave also better correlation, it had been decided to use it. It was hoped that when the effects of quantity and temperature were fully investigated, it might be possible to get a single constant to represent the full dynamical effect of silt on the movement of water.

A different line of attack on this silt problem suggested itself when it was considered that the characteristic of the flow of water in channels that kept silt in motion was turbulence. In Part I of this paper it had been shewn how the distribution of silt varied with the state of turbulence in the canal, so that if turbulence could be detected and analyzed it would be easier to get a single constant to represent the full dynamical effect of silt movement in canals. Parallel experiments on this line might profitably be started in future.

It was inevitable that comparison would be made between the relationships obtained in this paper and those proposed by Mr. Lacey. Dr. Bose anticipated some of these specially as Mr. Blench's paper,

which was to be discussed on the same day, was supposed to annotate Mr. Lacey. According to Mr. Blench the formula

$$\text{“ } V = 16\sqrt[3]{R^2 S}$$

was *the relation* and if it holds all hold ". The author wished to shew if that was the case from the data given in Table I. If one started the analysis without any prejudice, one would obtain the 'Regression Line,' to fit in with the data, as given by

$$\frac{V}{\sqrt{R}} = 2{\cdot}5 \times S^{\frac{1}{10}}.$$

This relation was dynamically sound as it was uniformly acknowledged that in all model experiments V was taken to vary as $\sqrt{R}$ and, moreover the correlation co-efficient was very high, as much as 95 p. c. The only relation of Mr. Lacey, according to Dr. Bose was perfectly sound, was

$$P = 2{\cdot}67\ Q^{\frac{1}{2}}.$$

From these data one could get 2·8 instead of 2·67. The correlation in this case was very high, as much as 99·5 p. c. This was to be expected as the quantities that were involved could be measured very accurately. There was a slight variation in the constant 2·8—with these data it varied from 2·8 to 3·0, but he had come across channels in which it varied from 2·5 to 3·0. The author thought this was due to hydraulic inertia of all channels. Perhaps it might be thought that this was due to silt, but strange enough, silt did not at all improve the correlation between P and Q, which remained still at 99·5% after silt was introduced as a third variable.

All the other relationships of Mr. Lacey involved f and as f was no silt characteristic, though it was called silt-factor, they could not be compared with the relations deduced in the paper. He said he would go more into details about this in Mr. Blench's paper.

Before concluding, Dr. Bose pointed out that the main achievement of this paper had been to show from a strict statistical analysis that silt was a predominating factor in determining the regime of channels. Though this idea had been in the air for a long time it was the first time that this had been proved from a set of very carefully collected hydraulic data and it was hoped that as the work was extended in future, the problem of the regime of channels flowing in their own silt would be solved completely.

Dr. **V. I. Vaidhianathan** said that, in 1933, a paper was read before the Punjab Engineering Congress on " Optical Lever Siltometer ". During the last three years about 3000 silts from thirty different sites

had been analyzed. This made 100 silts for each site. As a result of statistical analysis of these data, some relations were presented in the paper, which in the words of the author himself, "are frankly empirical and have not got the sanctity of natural laws." They would remain so, till it was known how to measure that which caused the silt to move, (*i.e.* turbulence). It might be a difficult task to measure it, but that was the starting point of any argument on silt movement. Since there was not much known about the latter, the equations on silt movement or regime conditions were bound to be empirical.

Regarding the number K, the so-called Schocklitsch number, the speaker said that Dr. Schocklitsch himself had put forward the number with a sufficient number of apologies. It was not unique: it was connected with the mean diameter by a simple relation. The number could be obtained directly from the photograph taken in the optical lever siltometer. The curves, however, told much more, but to represent the curve in an equation was rather difficult. So some convenient index had to be taken.

The number, however, had an experimental basis, as it was taken from the analysis curves.

MR. **Blench** said that in the presence of Mr. Lacey, he did not wish to enter into a detailed defence of the Lacey theory for which Mr. Bose now proposed a substitute but he, merely, wanted to point out the more obvious defects of that substitute. In doing so he recorded his appreciation of Dr. Bose's attempting a very hard task, starting from the very difficult beginning of deducing laws of channel flow from the imperfectly understood properties of silt, and also of his making observations of his own. Although these observations were open to some criticism they were, on the whole, ably done. It was unfortunate that the Lower Chenab Canal observations were of small value, because of the deliberate silt starvation put into effect at Khanki just before Dr. Bose started observing *vide* Mr. Khosla's paper. Then again his Table III results, obtained from various Divisions were worthless. On the whole he had made quite a good job allowing for the fact that some data was wrong, and the essential facts were not known to him.

His new silt factor K was unsuitable for analysis. For a uniform 0·6 mm. diameter it was infinite. Also for a 1·2 mm. diameter, say, it was easy to get the same K as for 0·6 mm. diameter, although the coarseness is double. Finally it would be obvious that K being only $d/(0{\cdot}6-d)$ could not tell more than d. The only reason he got any results at all was that over the small range of his experiments d was about $0{\cdot}29\ K^{\frac{1}{2}}$, and the use of this in his formula (1) would give a bad approximation to the Lacey Slope formula.

By eliminating K between his formulae (1) and (2) Mr. Blench got $V = 52{,}500\ RS^{4/3}$ which must be his test formulae for regime;

an alternative to Lacey's test formula $V=16\sqrt[3]{R^2S}$. The speaker had prepared a diagram (Fig. VIII) showing Dr. Bose's results plotted as log. V against log. $RS^{4/3}$, S being, for convenience, slope, x 10^4. It would be seen that the Table III results were nowhere near his regime line—so it was unfair of him to criticize Lacey on what could also be used to criticize himself, were it correct. As for the Lower Jhelum and the Lower Chenab Canal points, they lay on entirely different lines. So all that Dr. Bose had done was to get a mean relation to fit the Lower Jehlum Canal, which was in regime, and also fit the Lower Chenab Canal which was not. The result was useless for either.

The Diagram of log. V plotted against log R^2S (Fig. VIII) with the Lacey regime line drawn, shows that the Lower Jhelum Canal results lie closely on the line, and the Lower Chenab Canal ones are scattered about it, but not on a radically different line.

Mr. **Gerald Lacey** remarked that Dr. Bose was to be congratulated on a very interesting and valuable paper. There was no doubt that the silt distribution curves obtained throughout the year were of real value in illustrating the annual silt cycle.

He did not agree with Dr. Bose that the Schocklitsch number K was superior to 'm' the average particle size, "from physical considerations". The number K was clearly a real characteristic of silt since it was so closely associated with the average diameter but as a fact, K could tell nothing about the mix that 'm' did not tell. From Fig. IX(*a*) it was clear that the ratio A/B was none other than the ratio $\frac{m}{\cdot 6-m}$. That meant for one value of K there was only one value of 'm,' and for one value of 'm' only one value of K. K was a discontinuous function and did not lend itself to simple empirical equations of exponential form. It could be urged very properly that a good correlation had been obtained with K but this was due to the fact that within the limits of K=0·5, K=2·0, the corresponding value of 'm' was given approximately by the expression $'m'=\cdot 29\,K^{\frac{1}{2}}$. That is to say that in Dr. Bose's equations wherever K appeared it should be replaced by 'm.' Now 'm' clearly had dimensions, and this meant that the fact that K was dimensionless was of no great merit. A dimensionless number of value should result from dimensional analysis. Thus the Chezy, Froude and Reynolds numbers had a validity denied to K.

To the speaker, Mr. Lacey, it appeared that a modified Schocklitsch number was required to define mix.

Thus in Fig. IX (*b*), K was defined merely by the distance of the centroid from the left hand side divided by 0·6 minus that distance. Provided the centre of gravity remained at the same point, the shape which was characteristic of the mix, could change.

He suggested that the average diameter 'm' should be retained for statistical analysis and if it was desired to define mix this could be done with a new number K equal to A^1/B^1 as in Fig. IX (*c*). This number would also be a dimensionless ratio and independent of the average diameter. The Schocklitsch number was a simplification, of that there was no doubt ; but it was not really possible to obtain one ratio that could tell both diameter and mix at the same time. The distribution curves conveyed the information visually, but K was faulty as a mathematical presentation of what the eye saw.

However, whether K was employed or 'm' which appeared preferable, there was no doubt that Dr. Bose had succeeded in directly correlating a silt characteristic based on many actual measurements with the hydraulic variables, slope, discharge, and shape, and that was a real achievement.

Dr. Bose claimed merely that the relationships were empirical and that decision was wise. It would appear most necessary to increase the number of channels observed.

Dr. Bose had not found it possible to correlate the silt factor, which was proportional to V^2/R and that was not very surprising. Table III was a collection of data, which Dr. Bose had not employed in his own analysis and it was doubtful whether it was of value. There appeared much evidence in the table itself that the channels were not in regime. Since, however, Dr. Bose himself had made no use of the table, the matter could rest there.

The speaker had intended his equation $f=8\sqrt{d}$ as a rough guide to the value of V^2/R to be expected with channel beds varying from large boulders and shingle to fine silt. There was no doubt that the equation served this purpose. It gave results of the correct order. With a very limited range of observations there were disturbing factors. One was the kinematic viscosity of the water, the other the silt mix. The manner in which the voids of the bed silt were filled would depend on the silt mix and this would seriously affect the internal friction of the Prandtl boundary layer.

The silt factor was none other than a simple proportional to the Froude number, and also entered the Chezy number. This meant that the ratio V^2/R was of importance. The ratio had always been used as a criterion of dynamic similarity. If the first paper written by the speaker had any merit it was that he had drawn attention to the fact that on Kennedy's channels, all carrying coarse silt, the ratio V^2/R was a constant, and on the Madras canals, carrying fine silt, the same ratio was also a constant, but numerically less.

There was thus an undeniable relationship between the ratio V^2/R and the Silt grade. The situation was greatly complicated by other variables, which included temperature effects, mix, and colloids.

He was very interested to see that Dr. Bose had confirmed the relationship that he, the speaker, had produced some years ago,

$$P = 2 \cdot 668\ Q^{\frac{1}{2}}$$

It would appear at first sight that this could be written as

$$P^2 \propto PRV$$

and that the relationship involved the shape factor

$$P/R \propto V.$$

From certain reservations made by Dr. Bose that did not necessarily follow and he, Dr. Bose, would doubtless have something to say on that point.

He, Mr. Lacey, felt that the solution of the problem of silt transport had been carried a step further but that much still remained to be done.

Mr. **Kanwar Sain** said that Mr. Lacey's formulae and diagrams had worked quite well for the usual remodelling of channels and the main ideas on the subject had been admirably summed up by Mr. Blench in his paper No. 187. One difficulty, however, remained throughout and that was that Lacey's 'f' had to be given more or less an arbitrary value from experience. In the paper presented by Dr. Bose he had tried to replace Lacey's formulae containing ' f ' by similar formulae which contained K, and K was given by Dr. Bose, an exact physical significance and thus his K was determinable if the quality of the silt were known. There was one great drawback, however, that his results were collected only from the Punjab canals, and his relations had not been tested on canals in other provinces like Madras and Egypt. Mr. Lacey's formulae were more general. It was not possible to equate Bose's K to Lacey's ' f ' without Q appearing in the equation. Dr. Bose had stated in his paper that all attempts to relate ' f ' to the quality of the silt had so far been fruitless. It appeared that the idea which several Engineers had from practical experience that 'f' depended not only on quality but on quantity of silt as well might be true. It was suggested that in connecting Lacey's 'f' or Dr. Bose's K quantity of silt should also be taken into consideration and not only quality. It might then be possible to make Mr. Lacey's and Dr. Bose's results agree. The problem of silt in the canals was so important that a systematic and whole-sale study of a few canal systems could perhaps be taken up with advantage in the Research Institute. During the investigations it might first of all be determined how much quantity of silt was entering the canal at its head and what was its grade. As a second step both the quantity and quality of silt as taken by each offtake on the way should be determined right up to the tail. The silt-withdrawing capacities of various offtakes should be connected to a common silt factor. Mr. Sharma's paper No. 189 showed that it was possible to design heads of distributaries with predetermined silt-withdrawing capacities, although Mr. Sharma's results appeared to him to be badly out on account of distortion in scale.

Replying to the discussion, DR. **N. K. Bose** said he completely agreed with Dr. Vaidhianathan that the relation derived in the paper would remain empirical until it was known how to measure that which caused the silt to move (*i.e.*, turbulence). He hoped Dr. Vaidhianathan would succeed some day in devising some apparatus for measuring turbulence in canal flow which according to him was the starting point of any argument on silt movement.

Mr. Blench objected to the inclusion of the Lower Chenab Canal data in the analysis. But of all the sites selected for observations that had been kept under close observation for over 30 months these sites on the Lower Chenab Canal had been the most steady. Silt starvation at the headworks at Khanki had very little effect on the regime of these sites till early 1935 when the sites nearest the head reach, *i.e.*, Main Line Lower 149,000 R. D., and Hafizabad Distributary began to be affected. It was the local fitting of silt-skimmers at the heads of the distributaries that effected them mostly. This was why the data given in Table IV had been used for analysis and comparison instead of those in Table I.

Data given in Table III were supplied by local Executive Engineers and they were not used for analysis or comparison of the main Lacey formulae. They were introduced as additional data supposed to be reliable for which values of 'm' and 'f' were both worked out. They referred to isolated observations on which no statistical analysis could be based.

Mr. Blench's contention that for a uniform 0·6 mm. diameter, K was infinite, was not fair as K was used to represent the mix or silt samples which in the case of uniform diameter was zero. He could not see how it was easy to get the same K for 1·2 mm. diameter as from 0·6 mm. diameter.

Mr. Blench's attempt to connect d to K by

$$d = 0{\cdot}29\ K^{\frac{1}{2}}$$

for a small range of d was obviously inspired by the following relation of Lacey

$$d \propto f^2$$

Relation (1) of the paper

$$S \times 10^3 = K^{\frac{1}{2}}/Q^{\frac{1}{4}} \text{ with this substitution becomes}$$

$$S \propto d/Q^{\frac{1}{4}}$$

$$\propto f^{\ 2}/Q^{\frac{1}{4}}$$

which was what Mr. Blench called a bad approximation to Lacey formula. But why introduce a parabola between d and K when a more exact relationship existed.

By eliminating K between his formulae (1) and (2) Mr. Blench got $V=52{,}500\ R\ S^{\frac{4}{3}}$ which he called the Regime formulae, whereas the Regime Formulae given by the author was $\frac{V}{\sqrt{R}} = 2{\cdot}5 \times S^{\frac{1}{10}}$ which as had been pointed out before had a very high degree of correlation.

About elimination the author stated that he had said enough in Appendix II of the paper.

Dr. Bose agreed fully with Mr. Lacey that K did not represent silt completely. The fact that K was limited within a certain range was obviously a drawback but could not vitiate the analysis so long as this fact was clearly understood and borne in mind. K was chosen for analysis in preference to 'm' due to the fact that it consistently gave higher correlation than 'm' and as such was superior to 'm'. The very derivation of the factor K was most probably responsible for it. Attempts were being made to represent the full effect of silt. Mr. Lacey's suggestions to represent the mix by A'/B' was tried but was not found suitable as it was very difficult from an experimental standpoint to fix the two tail ends of the curve.

It had been mentioned in the paper that it had not been possible to correlate 'f' with 'd'. This had not been possible not only from data given in Table III but also for other data given in Tables I and IV. Mr. Lacey as a matter of fact expected too much from his *f*. At one place he said "The silt factor was none other than a simple proportional to Froude Number" and at another place he made it proportional to $\sqrt{d}$. Though there was an undeniable relationship between V^2/R and the silt, it did not mean that there was an undeniable relationship between his *f* and *d*, as his *f* could be derived from so many other relationships given by him and all these values of *f* very seldom agreed with one another. In the various formulae in which his *f* entered, Mr. Lacey had tried to absorb in *f* all the other hydraulic variables that appeared in the formulae explicitly or implicitly. As an instance he cited the well-known Chezy relationship :

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

in which C is known to vary. Instead of this Mr. Lacey had written

$$V = 1{\cdot}1512\ \sqrt{fR};$$

so that instead of introducing two variables, C and S, Mr. Lacey had introduced one variable *f*, which would absorb in it all the hydraulic variables that appear explicitly in the Chezy formulae and also all that appeared implicitly there in C.

The drawback mentioned by Mr. Kanwar Sain about the data utilized in this paper being exclusively derived from the Punjab canals had also been realized by the author ; but as the author had to decide

between reliable data and extensive data, and specially because silt data were not available from anywhere else excepting from the Punjab, the author had to content himself with the Punjab data alone. About the utility of knowing the quantity of silt that was entering each canal system and also the silt withdrawing capacities of various off-takes, the author was in full agreement. Attempts were being made to extend the silt investigations on these lines.

Correspondence.

Mr. **C. C. Inglis** stated that the author's remarks on distribution curves and their significance were of great interest.

Mr. **C. G. Hawes** pointed out some time ago that there was a fairly definite dividing line between bed silt and the silt found in berms, which for Sind was about 0·08 mm. The author's figure of 0·06 mm. confirmed the earlier figure. Mr. Inglis could not understand the author's quoting Prof. Gibson's remarks of a few years ago about distortion when Dr. Obsorne Reynolds pointed this out in 1888. It was Lacey who first reduced distortion to formulae and explained its physical significance which he had since shown, was not distortion when considered in terms of hydraulic width and depth.

The author set out to show that 'f_1' in Lacey's initial regime formula $V=1{\cdot}1512\sqrt{f_1 R}$ differed from 'f_2' in $f_2^{\frac{3}{2}}=10^6.R^{\frac{1}{2}}S/370{\cdot}68$ "for sites that were considered to be in regime by the local Executive Engineers"; and, having shown that there was a considerable difference, added "These figures speak for themselves." This line of criticism would be objectionable on several grounds. Firstly the author did not apply a similar test to his own formulae. Had he done so he would have found as would be shown later that Lacey's formulae fit the data considerably better than his own formulae; but the main objection was the unjustifiable assumption that channels were in regime if local officers considered them to be stable. Quite apart from the fact that both Lacey's formulae and the author's formulae indicated that few of these channels were in regime, Mr. Inglis believed that the opinion of local officers was often widely wrong on this question, because approximate stability frequently existed in channels which were far from final regime. On the other hand, the writer had yet to find a channel which was shown to be in regime by Lacey's formulae, and which was not stable; and up to 40 per cent of channels in Sind agree with Lacey's formulae with remarkable accuracy. The only fair test therefore was to compare results worked out by the two sets of formulae with actuals, and see how each fitted.

Lacey's regime criterion formula was

$$V=16{\cdot}02\,R^{\frac{2}{3}}\,S^{\frac{1}{3}}$$

and

$$C_L=V/16{\cdot}02\,R^{\frac{2}{3}}\,S^{\frac{1}{3}}$$

gave the degree of divergence. The formula might also be written as

$$V = 16{\cdot}02\ R^{\frac{2}{3}}\ S^{\frac{1}{3}}\ (f_1/f_2)^{\frac{1}{2}}$$

or $C_L = (f_1/f_2)^{\frac{1}{2}}$ and f_m had been taken $= \sqrt{f_1\ f_2}$

A criterion formula could also be worked out for the author's formulae:

$K^{\frac{1}{2}} = Q^{\frac{1}{4}}\ S \times 10^3$ .. .. .. (1) of Bose.

and $P = 2{\cdot}67\ Q^{\frac{1}{2}}$ (Lacey) .. .. (3) of Bose.

so $P = 7{\cdot}1182$ R. V. & $Q = 7{\cdot}12$ (R. V.)^2

so $K^{\frac{1}{2}} = 1{\cdot}634\ R^{\frac{1}{2}}.V^{\frac{1}{2}}.S \times 10^3$

also $P/R = 7{\cdot}1182\ V = K^{\frac{1}{2}}/S^{\frac{1}{3}}$ .. .. (2) of Bose

so $1634\ R^{\frac{1}{2}}.V^{\frac{1}{2}}.S = 7{\cdot}1182\ V.S^{\frac{1}{3}}$

or $V = 52{,}690\ R.\ S^{\frac{4}{3}}$ ..Bose criterion formula (B) which would be compared with

$V = 10\ R^{\frac{2}{3}}.S$ Lacey criterion formula (L)

C_L being the co-efficient for the Lacey formula and C_B for Bose formula.

It would be seen from both Tables (A) and (B) that Lacey's formula stood the test better than the author's. Thus in Table A (counting ±3 per cent as in regime) only 1 channel could be in regime according to the author compared to 4 according to Lacey (out of 22) and in Table B, 5 according to the author and 8 according to Lacey (out of 26).

Supposing, however, for the sake of argument, that the author had demonstrated that there was no connection between 'f' and 'm', would this matter from the practical point of view? Did the author really suggest that any one was going to design or remodel channels relying on silt samples? One had only to look at Table 8 to see how foolish this would be; because 'K' values varied from 2·12 to 0·49 for a single Canal (the Lower Chenab) and even in the case of the Lower Jhelum, which was in fair regime, K varied from 1·38 to 0·6 for different channels. On the other hand it was easy to estimate f_m for existing Canals and fix values for new Canals and it was clearly desirable to design for regime conditions for all channels except a few where local conditions would make this impossible; but even then it would be easier to estimate C_L rather than K).

In remodelling it was obviously safer to adopt Lacey and known values of S, R and V, which would give definite values for f_1 and f_2, and so make it possible to design with a high degree of accuracy, than to trust to silt samples and use formulae which gave only approximate results.

In this connection attention was called to Table C, which showed all dimensions for the channels shown in the author's Table IV according to the author's formulae and actuals. These were based on Q and K in the former and Q and f_m for Lacey dimensions, that is to say, 'divergence from regime had been ignored in the case of Lacey figures, f_m being assumed to be uniform throughout the Canal system; in spite of this and the fact that the author's formulae were worked out from this very data, whereas Lacey's formulae were worked out on other data the agreement of Lacey's dimensions with actuals was markedly better than the author's, especially in the case of velocities. In other words the author had completely failed to break down the practical value of the Lacey formulae even on his own ground, and when it came to analyzing the condition of a canal system the Lacey formulae were markedly better, being based on a much wider range of discharges and conditions.

Discussing the author's reference to Schocklitsch number Mr. Inglis stated that he had omitted 'm' from Tables I and IV and 'K' from Table III, so that the close relationship between the two (for the range of data presented) was not apparent. Actually, however, $K=A/B$; and as A was a measure of 'm' and $A+B=0{\cdot}6$,

$$K=\frac{m}{{\cdot}6-m} \text{ or } m=\frac{{\cdot}6\,K}{1+K}.$$

The 'm' values corresponding to the K values shown in Table IV had been shown (in Table C) thus making comparison easy; but Figure A, which showed the relationship between 'm' and 'K' on log. paper indicated the relationship much more clearly. From this it will be seen that if the silt were uniformly 0·06 mm. diam., K would be infinity. It would also be seen that an exponential formula in terms of 'm' almost coincided with the 'K' curve for the range of the data, and coincided still closely if the extreme values of K—which in any case did not agree well with the formula—were omitted. The author could in fact replace K by 'm' in his formulae, which appeared to be the main reason why the results, using K, were not more widely out.

The author called the Schocklitsch number a 'non-dimensional quantity'; actually it was merely 'an arbitrary ratio' which, in effect represented divergence from a standard silt distribution, because fixing the maximum silt grade at 0·6 mm. was equivalent to fixing the silt standard. This was objectionable on two grounds. Firstly, it was wrong to fix an arbitrary silt standard for all the canals in the Punjab. Each canal should have its own standard. Secondy, the Schocklitsch number exaggerated the effect of large divergences from regime (normal silt). Thus, with standard fixed by the 0·6 mm. limit, if all the silt were of 0·6 mm. grade, K would be infinity and for a coarser silt K would become negative; whereas if the arbitrary standard were taken 1·0 mm. a widely different result would be obtained for the same silt. This was obviously absurd.

It had long been the writer's opinion that Lacey's 'final regime indicated a natural distribution of silt (normal population), and that there should be two silt factors—the one indicating the standard grade and the other 'divergence from normal.' The former would be different for each canal; but should for practical reasons be uniform for each canal, if this be possible; while the latter would represent divergence from normal. Working on these lines f_m and C_L represent 'normality' and 'divergence.'

It would be seen from Tables A, B and C that though f_m varied somewhat, the mean value was clear for each canal provided there was adequate data available. Mr. Inglis also emphasized that in Table C the dimensions were worked out using a mean value for f_m, *i.e.*, ignoring divergence.

As the Lacey formulae were all for final regime, $f_1=f_2$. It was interesting to restate the formulae in terms of f_1 and f_2.

$$S_L = f_1^{\frac{1}{6}} \cdot f_2^{\frac{3}{2}} \cdot \frac{\cdot 1}{1856\ Q^{\frac{1}{6}}}$$

$$R_L = \frac{1}{f_1^{\frac{1}{3}}} \cdot 0{\cdot}47326\ Q^{\frac{1}{3}}.$$

$$V_L = f_1^{\frac{1}{3}} . 0{\cdot}79198\ Q^{\frac{1}{6}}.$$

Calling $f_m = \sqrt{f_1 \cdot f_2}$ and $C_L = \sqrt{f_1 / f_2} = f_1 / f_m = f_m /$ these formulae might also be written

$$S_L = \frac{f_m^{5/3}}{C_L^{4/3}} \cdot \frac{1}{1856\ Q^{\frac{1}{6}}} \qquad S_B = K^{\frac{1}{2}} \cdot \frac{1}{1000\ Q^{\frac{1}{4}}}$$

$$R_L = \frac{1}{(f_m C_L)^{\frac{1}{3}}} \cdot 0{\cdot}47326\ Q^{\frac{1}{3}} \qquad R_B = \frac{1}{K^{\frac{1}{3}}} . 0{\cdot}2668\ Q^{\frac{5}{12}}$$

$$V_L = (f_m C_L)^{\frac{1}{3}} . 0{\cdot}79198\ Q^{\frac{1}{6}} \qquad V_B = K^{\frac{1}{3}} . 1{\cdot}4048\ Q^{\frac{1}{12}}$$

If (purely for analysis) the two formulae were assumed to give the same results, then from either the R or V formulae

$$\left(\frac{K}{f_m C_L}\right)^{\frac{1}{3}} = 0{\cdot}5638\ Q^{\frac{1}{12}}$$

or $K = f_m C_L$ or $= f_m$ (if in regime)

when Q=970 cusecs.

A few further points might be noted :

(*a*) Lacey's slope formula might be written,

$$S_L = \frac{f_1^{\frac{5}{3}}}{C_L^{3}} \quad \frac{1}{1856\ Q^{\frac{1}{6}}}$$

This explained why the formula gave such divergent results when based on f_1 and the author, by using this formula for calculating slope by Lacey (Col. XIII of Table IV) cubed the divergence.

The correct formula would be

$$S_L = f_2^{\frac{5}{3}} . C_L^{\frac{1}{3}} \frac{1}{1856\ Q^{\frac{1}{6}}}, \quad \text{not} \quad S_L = f_2^{\frac{5}{3}} . \frac{1}{1856\ Q^{\frac{1}{6}}}$$

(*c*) In this data K varied roughly as $Q^{\frac{1}{5}}$ and " m " as $Q^{\frac{1}{10}}$ for both the canals. Mr. Inglis wanted to know if this was due to

(*i*) a reduction of silt grade—and if so whether temporary or normal ;

(*ii*) the method of sampling not giving a truly representative sample of the silt in motion ; or

(*iii*) the operation of a physical law.

Whatever might be the cause, it had a considerable effect on the author's formulae.

The data as collected, seemed to the writer to be of great interest and value and he suggested that it should be made available—as far as possible—to research workers.

As pointed out by the author and emphasized by the writer, the difficulties in the way of this investigation were very great ; because few large channels were run continuously under uniform conditions of discharge and silt, and, in the case of large channels, afflux which spoilt results, could rarely be eliminated—thus, 2 channels of Table IV, Serial Nos. 1 and 2, were obviously not in regime, though they might have been approximately stable.

It was important to select some canals with coarse silt, and others which carried fine silt—so that a wide range of silt conditions could be tested. The " normal silt distribution " of the Upper Bari Doab appeared to be considerably coarser than that of the Lower Chenab. Data was inadequate to draw any conclusion, but it was noticeable that the Lacey formulae fitted the data well while the author's did not.

It was obvious that unless the standard of reliability of the data could be markedly improved it would be necessary to collect a mass of data so as to eliminate errors due to the difficulty of assessing true final regime ; and even then, unless the range of silt and discharge could be widened, and some method of evaluating ' normal silt distribution ' and ' divergence from normal ' evolved, blurred and unreliable results must be expected. As a first step it was suggested that no channel should be assumed to be in regime unless a specially selected Canal Officer, unconnected with the investigation, agreed, after a critical analysis of facts, that the channel was stable and that this stability appeared to be due to the channel *having reached regime.*

Dr. **N. K. Bose** found Mr. Inglis's line of arguments, in discussing the paper, the same as adopted by Messrs. Lacey and Blench. These had been dealt with mostly in reply to their criticism. Only one point required attention. Mr. Inglis derived a relationship.

$$(B) \qquad V = 52{,}690 \quad RS^{\frac{4}{3}}$$

and called this Bose Criterion formula. As the author pointed out in introducing the paper the criterion formula if it could be so called was

$$\frac{V}{\sqrt{R}} = 2{\cdot}5\ S^{\frac{1}{10}}$$

so that the relationship (B) given by Mr. Inglis was not correct and all the conclusions derived from it, therefore would fall through.

The main portion of Mr. Inglis's discussion was about the various formulae proposed by Mr. Lacey in two of his papers on Regime channels. Mr. Inglis had introduced a departure in the treatment of Lacey formulae. As f_1 and f_2 were fundamentally and evidently different he introduced a new silt factor

$$fm = \sqrt{f_1\ f_2}.$$

Introducing this in the two equations giving f_1 and f_2 we would get

$$f_m = \frac{V}{R^{\frac{1}{3}}} . S^{\frac{1}{3}} \times 12{\cdot}1.$$

$$\text{Or } V = \frac{fm}{12{\cdot}1} \cdot \frac{R^{\frac{1}{3}}}{S^{\frac{1}{3}}}$$

which was certainly different from Lacey's relationship

$$V = 16{\cdot}02\ R^{\frac{2}{3}} S^{\frac{1}{3}}$$

Mr. Inglis had proposed a modified form of the Lacey criterion formula in which he introduced f_1 and f_2 in the above relation and got

$$V = 16{\cdot}02\ \ R^{\frac{2}{3}} S^{\frac{1}{3}} . \left(\frac{f_1}{f_2}\right)^{\frac{1}{2}}.$$

The author referred to his discussion of Mr. Blench's Congress Paper No. 187 in which he pointed out that the constant of the Lacey criterion formulae approximated to 16 as f_1 and f_2 approached each other. If $f_1 < f_2$ it was less than 16 and if $f_1 > f_2$ it was greater than 16. Mr. Inglis had evidently utilized this remark and introduced in Lacey relation $\left(\frac{f_1}{f_2}\right)^{\frac{1}{2}}$ which he called the "degree of divergence" so that the constant in the Lacey criterion formula was now $16\left(\frac{f_1}{f_2}\right)^{\frac{1}{2}}$, and when $f_1 < f_2$ the constant was less than 16, for $f_1 = f_2$ it was equal to 16 and for $f_1 > f_2$ it is greater than 16.

This made one point clear. Mr. Inglis admitted that there were two 'f's in Lacey formulae. This would clear the atmosphere considerably and it was hoped that Mr. Inglis would see that there were more 'f's than two in Lacey relationships. Would Mr. Inglis then agree to propose

$$f_m = \sqrt[n]{f_1, f_2 \ldots\ldots f_n} \; ?$$

By this Mr. Inglis would make the estimation of a single value silt factor f_m for a channel or a whole system of channels very easy and quite simple. But this had two points against it :—

(1) f_m was an arithmetically derived quantity and had no physical significance, at least no physical relationship with silt.

(2) The geometrical mean f_m proposed was certainly inferior to the arithmetic mean $\frac{f_1+f_2}{2}$ unless there be any specific reason for it.

Mr. Inglis stated " It has been long the writer's opinion that there should be two silt factors" f_m and C_L where

$$f_m = \sqrt{f_1 \; f_2}$$

$$C_L = \left(\frac{f_1}{f_2}\right)^{\frac{1}{2}}$$

How would he work out C_L when there are more than two 'f's ? Mr. Inglis asserted that the Lacey formulae were all for the final regime. Mr. Blench in his Punjab Enigneering Congress Paper No. 187 called some of them as belonging to initial regime and some to final (and therefore initial) regime. The author asked as to who could be the best interpreter of Lacey.

Mr. Inglis had re-written Lacey relationship

$$S = f^{\frac{5}{3}} / 1{,}788\ Q^{\frac{1}{6}}$$

in this form

$$S = f_1^{\frac{1}{6}} \cdot f_2^{\frac{3}{2}} / 1856\ Q^{\frac{1}{6}}$$

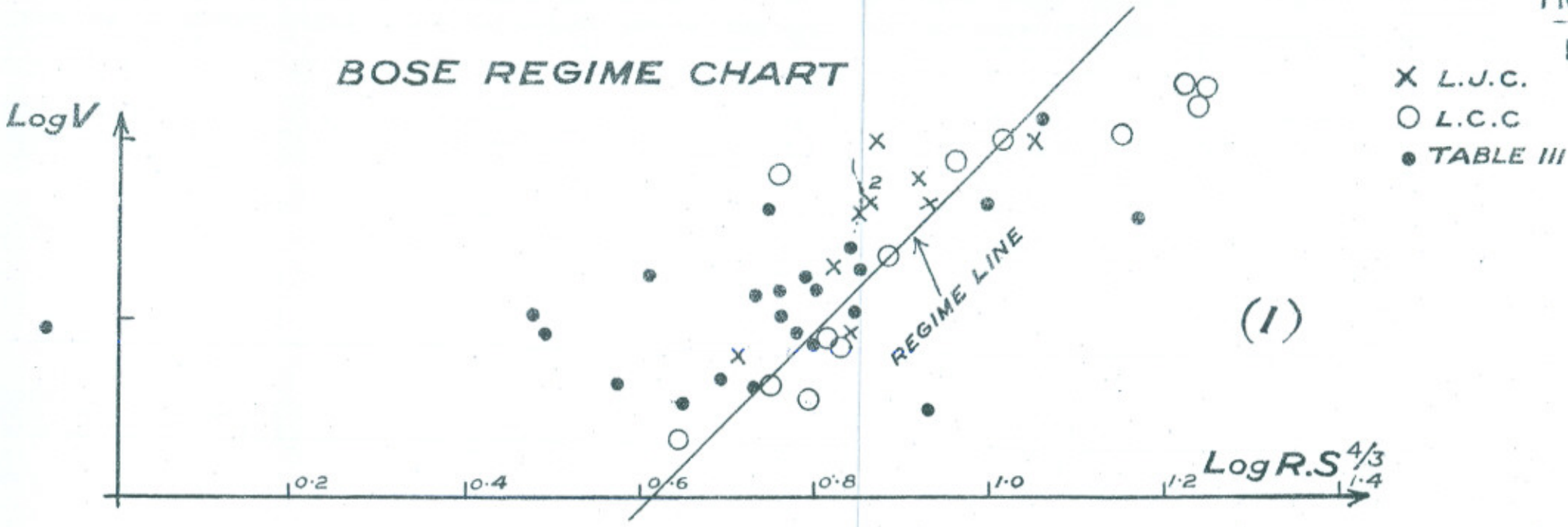
How had he arrived at this distribution of powers for f_1 and f_2? If he had distributed them differently he could have arrived at any other final conclusions diametrically opposite to his present ones. Not being content with this Mr. Inglis introduced his new silt factor C_L and got

$$S = \frac{fm^{5/3}}{C_L^{4/3}} \quad \frac{1}{1856\ Q^{1/6}}$$

and not the original Lacey formulae,

$$S = f_2^{\frac{5}{3}} \cdot \frac{1}{1856\ Q^{\frac{1}{6}}},$$

Thus there would be two sets of relationships, the first as was originally proposed by Mr. Lacey and the new one as modified by Mr. Inglis. He asked if Mr. Lacey accepted all these modifications.


BOSE REGIME CHART
Log V
X L.J.C.
O L.C.C
● TABLE III
REGIME LINE
(I)
0·2
0·4
0·6
0·8
1·0
1·2
1·4
Log R.S 4/3

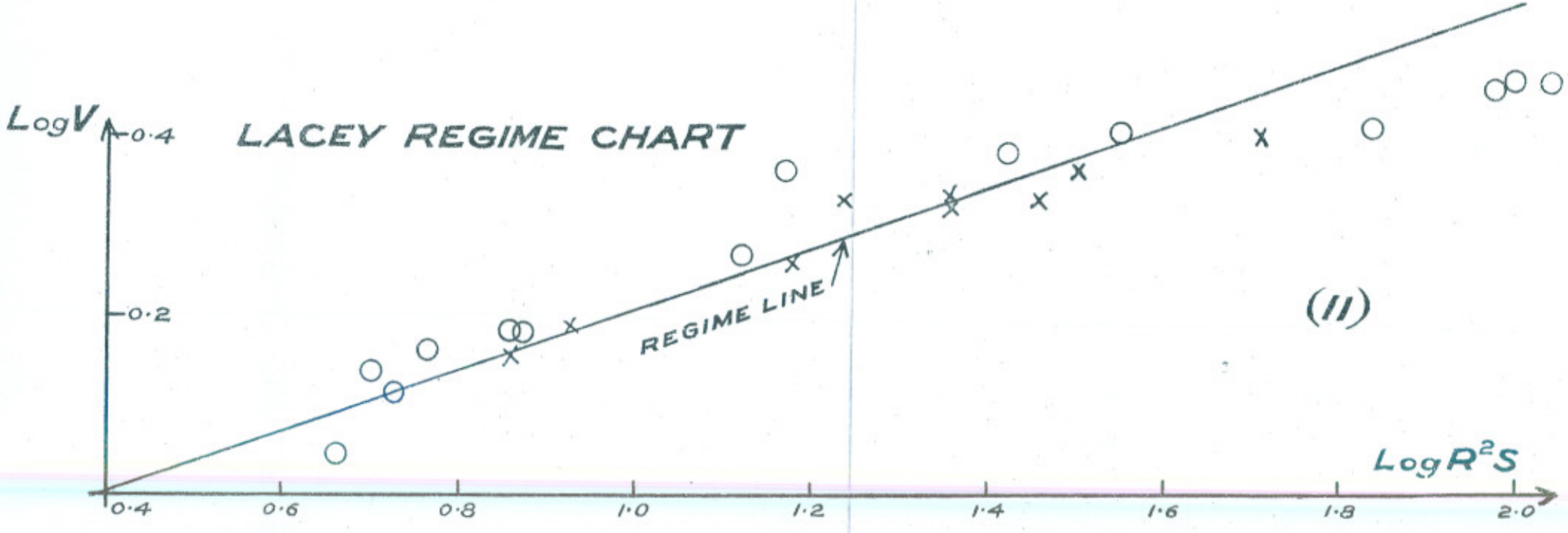

Log V
0·4
0·2
LACEY REGIME CHART
REGIME LINE
(II)
0·4
0·6
0·8
1·0
1·2
1·4
1·6
1·8
2·0
Log R²S

FIG. IX

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