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AN OPTICAL LEVER SILTOMETER.

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Introduction.

In this paper we discuss a new siltometer that has been constructed in the Irrigation Research Institute, Lahore ; for an accurate analysis of silt. It is a well-known fact that the knowledge of the size distribution of silt is one of the most important in canal engineering. The behaviour of silt in a canal largely determines the cost of maintenance and seriously affects the discharge. When the silt movements are large, the channels silt up altogether necessitating a new design and expensive work to put the channel in a condition to deal with the silt discharge. When the silt movements are small there are many minor troubles which affect the discharge and these are questions which have been baffling canal engineers. For any progress regarding the silt problem, it is *a priori* evident that the nature of silt should be known and yet it is its nature that has been the most obscure so far.

There were attempts made in the past to develop some sort of apparatus to study size distribution of silt, but they have not been successful. There has also been some confusion in using the apparatus developed for studying the size distribution of soils to analyse silts. It is necessary therefore to make a brief mention of some of the most important attempts in the construction of apparatus for the study of the size distribution of soils, and of their limitations.

The most recent one is that made by Dr. Keen and is generally known as the Oden-Keen Balance. In this balance, the rate at which soil from a suspension deposits on the scale pan of a sensitive balance is measured automatically and the sedimentation curve thus obtained is made the basis for the study of the size distribution. It is not necessary for us to go into the details of the elaborate arrangements which Dr. Keen and his co-workers adopted. The reader may refer to the article in the Proceedings of the Royal Society ; A. 106, 33 (1924) for further information. The apparatus was not successful for soil analysis and the authors themselves mention that it was mainly intended for analysis of particles, the sizes of which were less than 30 μ ($1\mu = \frac{1}{10}$ mm.). This size is finer than the finest berm silt.

Another attempt was made by Wiegner in Germany as early as 1918. Since we are adopting the principle of Wiegner, it may be worth while to describe in a few lines, his apparatus and its limitations. Wiegner's apparatus depends upon the recording of the rate of change of pressure at a particular point in a settling suspension. His apparatus consists of two long glass tubes one of which is narrow and the other wide. The narrow tube is fixed or attached to the wider one at a short distance from the bottom and the tubes are supported vertically. There is a stopcock at the junction of the two tubes. The tubes are first filled with water and the stopcock is closed. Water in the wide tube is replaced by a soil suspension and the stopcock is opened. The level in the narrow tube would rise, because the density of the suspension in the larger tube is increased. When the particles settle and pass across the section of the side manometer tube the pressure is reduced and the water meniscus in the narrow tube slowly falls. The rate of fall of this meniscus is magnified and recorded automatically. This becomes a measure of the size distribution.

There are many defects in the method. The first is that the liquids in the two tubes are different in density and on opening the stopcock they get partly mixed. Cross currents are set up between the two tubes and disturb the smooth falling of the particles. If the particles are coarse and consequently settle down quickly, there is the most serious difficulty that the water meniscus will refuse to respond rapidly to the small changes of pressure. There will be a considerable lag in the fall of the water meniscus in the narrow tube and only a distorted sedimentation curve could be obtained. It is also difficult to obtain a high magnification of the fall of the water meniscus.

When Wiegner developed the apparatus he had mainly in view the analysis of soil suspensions. In the case of silt, the particles are coarse (about five to ten times the diameter of soil particles), and the method could not therefore be used successfully for analysing silts. Some preliminary attempts had been made in the Institute to use Wiegner's apparatus for analysis of silts and for reasons stated above the method could not succeed.

In the case of soils, mention may also be made of the hydrometer method which is capable of approximate results. In the case of silts, this method is not useful, since the silt settles down quickly and the hydrometer cannot respond truly to the dynamic state in the silt suspension.

In the Punjab, there has been in use a simple apparatus called Kennedy Siltometer. This is a long tube about 4 inches in diameter and tapers at the bottom. A glass cylinder of $1\frac{1}{2}$ inches diameter is attached to the bottom of the siltometer. The siltometer is filled with water and a very large amount, about 650 grammes of silt is dropped into it and the rate at which the graduations in the glass cylinder are filled up is observed by a stopwatch. An account of this and the experiments

carried out by Kennedy are given in the Punjab Irrigation Branch Papers No. 9 ; " Report on the deposit and scour of silt in the main line, Sirhind Canal, and on the silt experiments 1893-1898." This apparatus while admirably simple is not capable of trustworthy results. As a pioneer attempt made in the last century, it certainly must occupy an important place in the history of the development of such apparatus. To use that apparatus to-day for analysing silt will not lead to any advancement. The errors are indicated in a subsequent section.

It will be seen from what has been said above that there is no reliable method of studying the size distribution of silt. Arbitrary classifications of silt into clay, fine silt, silt, coarse sand, etc., will not enable us to go any step further in treating the silting and scouring problem. With these objects in view we began experiments to evolve an apparatus for the accurate study of the size distribution of silt.

Theory of the Method.

Before going into the details of the apparatus, it may be instructive to understand the theory on which it is based, and how the observations enable a distribution curve of the silt to be obtained.

Let us suppose that we introduce a thin layer of silt into a long and wide tube containing a liquid and consider the pressures at a depth ' h ' below the free surface ; ' h ' being the depth after the silt is dropped ' h ' is supposed to be large compared with the thickness of the dropping layer of silt.

The total pressure at the section under consideration is given by

$$P_h = Ahd + v_s d_s - v_s d$$

where

A is the area of cross-section of the tube.

h is the depth below the free surface after the silt is dropped.

v_s is the volume of silt above the section.

d_s is the density of silt.

and d is the density of the liquid in the tube.

In this expression, Ahd represents the pressure on the whole surface due to the weight of water standing on it ; $v_s d_s$ is due to the weight of the silt and $v_s d$ is the loss of weight due to buoyancy.

The silt particle falls in the viscous medium and after an interval depending on the size of particles, the whole of it will have passed down the point under consideration.

For the rate of variation of P_h with respect to time we obtain :—

$$\frac{dP_h}{dt} = \frac{d\,(v_s\, d_s)}{dt}\left(1-\frac{d}{d_s}\right)$$

A, h and d being fixed for any given apparatus and for any given liquid, are independent of t.

Since $\left(1-\frac{d}{d_s}\right)$ is a constant, $\frac{dP_h}{dt} = K\frac{dws}{dt}$

Where ws is the weight of the silt and is equal to $v_s d_s$, and K if equal to $\left(1-\frac{d}{d_s}.\right)$

Now ws consists of an infinite number of groups of particles of varying radii and we may conceive of these groups having weights w_1, w_2, etc., and radii r_1, r_2, etc.

According to Stokes' Law, the velocity V with which the particles fall in a viscous medium is a function of r. The density of silt particles is the same and therefore w_1, w_2, etc., may be written as $\frac{4}{3}\pi\ r^3{}_1 ds$; $\frac{4}{3}\pi\ r^3{}_2\ ds$....and so on. Hence if the experiment gives the time of fall and the corresponding weights, the radii corresponding to these weights could be obtained with the help of Stokes' Law.

As shown before, since $\frac{dP_h}{dt} = K\frac{dw_s}{dt}$; measurement of P_h is proportional to the measurement of w_s and the experiment may be arranged to give P_h as a function of t the time of fall.

In converting P_h as a function of r, from the corresponding time and Stokes' Law, we neglect the shape factor of the silt. The settling velocity according to Stokes' Law is taken and assuming the particle to be a sphere, the radius is calculated and defined as the equivalent radius. This has been the method used in soil analysis and at present there is no other way of conceiving the size distribution.

By suitable experimental arrangements, if we could obtain a curve relating P_h and t, then a curve relating P_h and r could be plotted from the former.

From P_h, r curve, we obtain $\frac{d\,P_h}{dr}$ for different values of r. This is done by drawing tangents to the curve at convenient intervals of r and a third curve is obtained between $\frac{d\,P_h}{dr}$ as ordinates and the corresponding r as abscissae. This curve is such that it meets the r axis when $\frac{d\,P_h}{dr} = 0$ *i.e.*, when P_h in the former curve runs parallel to the

r axis. Experimentally this would always happen till the first set of particles reach the section at 'h' and after all the particles in the silt have passed across the section. The $\frac{d\,Ph}{dr}$ curve must therefore meet the r axis at the maximum and minimum values of r in the silt. The total area of the curve is $\int_{r\ (\text{min.})}^{r\ (\text{max.})} \frac{dP_h}{dr} \cdot dr.$ and is enclosed between two points on the abscissae corresponding to the maximum and minimum values of r in the silt. The total area corresponds to the total weight of silt in the experiment. The fraction by weight of particles between any two radii r_1 and r_2 is given by

$$\int_{r_1}^{r_2} \frac{dP_h}{dr}.dr \Bigg/ \int_{r\ (\text{min.})}^{r\ (\text{max.})} \frac{dP_h}{dr}.\,dr$$

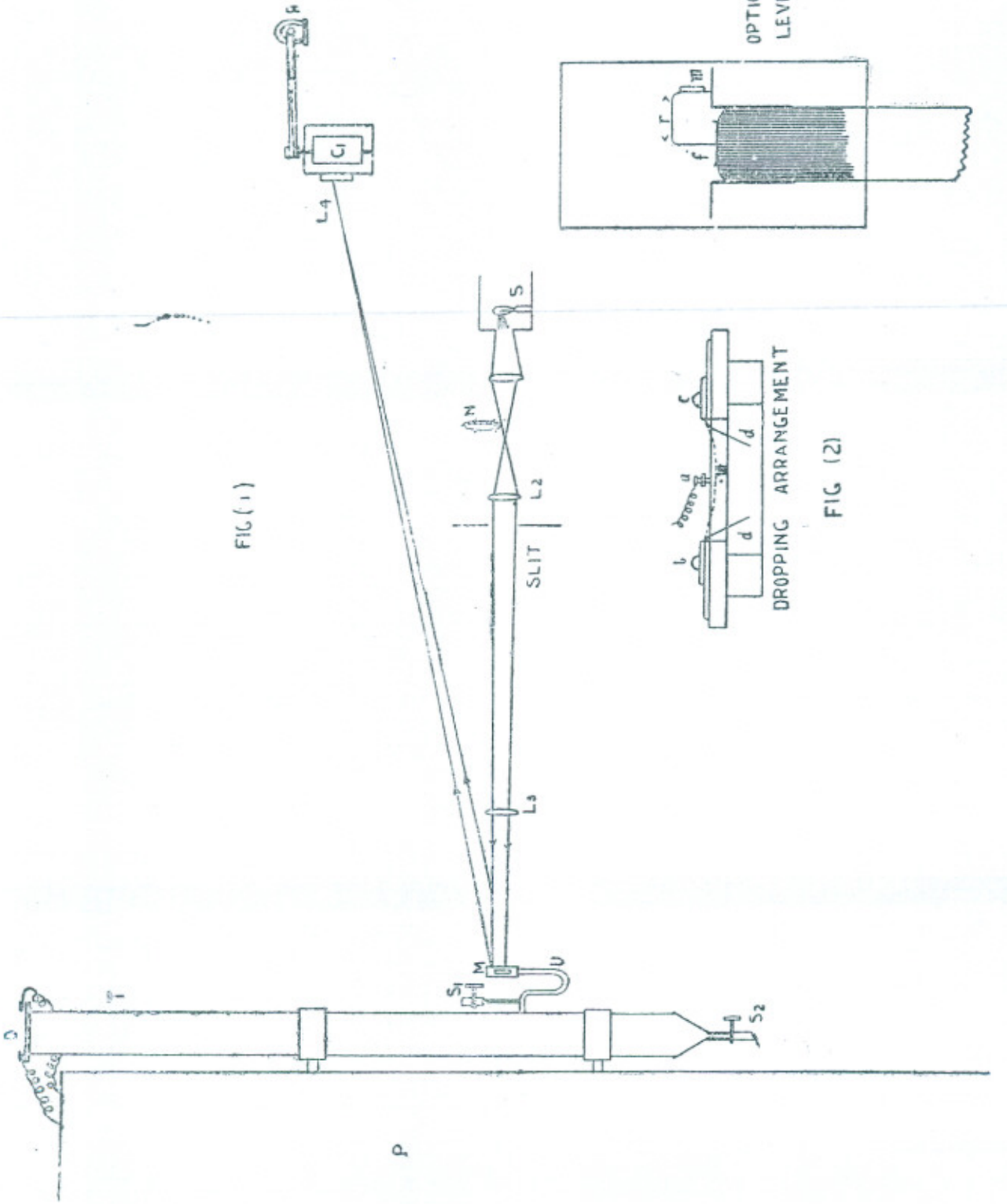
i.e., graphically the area enclosed between the ordinates corresponding to r_1 and r_2 expressed as a fraction of the total area enclosed by the curve.

It can be seen from the foregoing discussion of the theory that an experimental arrangement based on the same has three distinct parts. The first is the recording of the rate of change of pressure with time ; second, the magnification of the rate of change of pressure to enable the distribution to be known accurately and third, the dropping of the silt without a starting momentum. We describe below an apparatus constructed on the basis of the above considerations.

Description of the Siltometer.

In Fig. 1, T is a brass tube about 120 cms., long and having an internal diameter equal to about 7 cms. A small U tube of glass is sealed to T at a distance of about 82 cms. from the top. The side tube at the joint is slightly bent upwards to prevent any particle of the settling silt from entering the side tube. S_1 and S_2 are two stopcocks ; the former serves to remove any air bubble that might get lodged in the bend, when the tube is filled with water and the latter to

facilitate cleaning the tube T. The brass tube T is fixed vertically to a massive pillar.



The open limb of the manometer tube, U, is about 9 cms. long and 1 cm. in diameter, and the other short limb is slightly broader, fitting over the brass side tube. About half of the manometer tube is filled with very clean mercury and water is poured into the sedimentation tube, T. In the experiments described here, the free surface of water in the tube was 80·7 cms. from the cross-section at which the manometer tube is sealed, the level being measured from the centre of the cross-section of the manometer tube. The quantity of mercury is adjusted so that it stands 2 or 3 mm. below the top of the open limb.

If silt is now dropped into the sedimentation tube T, there is an increase of pressure. The mercury surface consequently rises and remains constant until the first particle has passed across the section of the manometer tube. Afterwards the mercury meniscus falls continuously, the rate of fall of this meniscus depending on the distribution. When all the silt has passed across the section of the manometer tube, the meniscus is again stationary, though the mercury level is different from the position it occupied before the silt was dropped. This difference is due to the presence of the silt which causes the free level of the water in the sedimentation tube, to rise by an amount depending upon the volume of the silt dropped. This is referred to in subsequent discussions as volume pressure to differentiate it from the weight pressure due to the silt. The latter is the varying factor which the experiment attempts to measure and corresponds to $\frac{d\,Ph}{dt}$ mentioned in the theoretical discussion.

In the experiments, the actual movement of the mercury was about 1/30 mm. due to the total weight pressure, and the rate of change of this with time when the silt particles pass across the section of the manometer tube is to be measured.

A very large magnification of the movement of the mercury meniscus is necessary for any practical measurement. This was secured by a specially constructed optical lever shown in Fig. 3. A broad brass ring which could be fixed along the manometer tube, supports two arms of an optical lever. The upper side of the ring is carefully planed and the two legs of the lever fit into two grooves in the same. '*m*' is a plane galvanometer mirror fixed to the lever. The third leg of the lever is soldered to a light nickel cup (*f*, in the figure) about 3 mms. in diameter and rests centrally on the mercury surface in the tube. The arm of the lever is about 5 mms. Very fine adjustments are necessary to fit the optical lever so that it is free to move. The optical lever is enclosed in a glass case as is shown at M in Fig. 1.

Simple calculations would now show that, if a spot of light reflected from M, is observed on a screen at a distance of 3 meters, it would appear to move through 4 cms., corresponding to the movement of mercury surface through $\frac{1}{30}$ mm. These were roughly the actual distances

used in the experiment. When the mercury surface moves up and down, the central leg moves with it, and tilts the mirror, causing a change in the direction of the reflected beam. This magnification was found to be sufficient, about 14 grammes of the sample of silt being required to make the spot of light move through about 5 cms. on the screen.

Depending upon the nature of the silt, the spot of light moves slowly at first, then the velocity increases reaching a maximum at some particular time and afterwards becomes slow and finally stops. For a quantitative analysis, the rate of movement of the spot is recorded automatically.

The recording mechanism is shown at C_1 in Fig. 1. A rotating drum carries a sensitised paper 44 cms. long and 10 cms. broad. A fine spot of light is focussed on to this by an optical system consisting of lenses L_1, L_2, L_3 and L_4. Since it is necessary to know accurately the time between the dropping of the silt and the arrival of any set of particles at the cross-section of the manometer tube, an automatic record of the time is made on the photographic paper. This is accomplished by interrupting the light at known intervals. As mentioned in the theoretical section, it is necessary to drop the silt quickly in a thin layer. In the case of fine silt which takes a long time to settle down, the dropping could be carried out without any special device. In the case of coarse silts, a mechanical dropper is used. This is shown in Fig. 2. A metallic ring is fixed with an ebonite plate having an opening nearly 6 cms. square and there are two aluminium shutters *d*, *d* which can open downwards when released. The two shutters are fitted with pads at *b* and *c* so that when they open, they do not produce any jerk. The shutters can be held in the closed position by a thin copper wire '*w*.' The required quantity of silt is placed on the shutter and the wire is fused by a current. This causes the silt to drop down in a quick stream from a height of a millimeter or two. However small this dropping is, it produces fluctuation of the surface of the mercury, but they die down in 3 or 4 seconds and therefore do not interfere with the results. This can be seen clearly in Fig. 4, where the wavy portion corresponds to the same fluctuations.

Method of Experimenting and Results.

The method of experimenting will be clear if we explain with reference to Fig. 4. When the drum rotates and no silt is dropped, the line AB is traced by the spot of light. As soon as the silt is dropped the spot of light shoots down and the line CC'D is traced until at D the first portion of the silt has reached the cross-section of the manometer tube. DEFG is the most significant portion, where most of the silt is settling down. The line KL corresponds to the final line when all the silt has passed the cross-section. We have now a sedimentation curve from which the distribution curve can be easily worked out as shown in the theoretical section. The heights of the various points of the spiral curve from the line KL is measured with a transparent scale and from

these the distribution curve is obtained. Such a distribution curve obtained from Fig. 4 is shown in Fig. 5. The silt whose distribution is shown in Fig. 5 was obtained from the Nasrana Distributary at R. D. 25,000. Fig. 5 is self-explanatory and the salient points can be seen from the curve without any further remarks.

Fig. 6 is the siltogram of a fine silt obtained from a water-course at the same R. D. at Nasrana and leads to the distribution curve shown in Fig. 7. The differences in the nature of the two distribution curves are interesting and remarkable. We do not intend at this stage to discuss the significance of the facts indicated by the curve and their possibilities. Until a large amount of data on silt analysis and other reliable hydraulic constants are obtained, nothing definite can be said.

The apparatus has been tested with silts and mixtures of known concentrations and has been found to work very satisfactorily. It is now regularly used to analyse silts from various canals.

Sources of Error and Precautions.

We may consider the various precautions that are necessary to obtain accurate results. The most important is that the mercury in the manometer tube should be clean. Any small scum and the consequent sticking of the mercury should be carefully avoided. The silt should be free from clay. The effect of the latter is to cause the silt particles to stick together.

Since the short column of mercury in the manometer tube responds rapidly to small vibrations, special mounting of the siltometer is necessary. At present, in the Institute, the siltometer is worked at night when road traffic has subsided. Though the siltometer is mounted on a massive pillar isolated from the floor, it has been impossible to work during the day due to surface vibrations.

Another point of importance is the limitations to Stokes' Law. When water is used as the medium for sedimentation, for silt particles larger than 0·1 mm. the law to be applied is not Stokes' but Goldstein's. This has been ignored in the past. For a silt particle whose diameter is nearly 0·3 mm. according to Goldstein's law, Stokes' Law would only give 0·22 mm., as the diameter. Many of the silts that we obtain in the Punjab canals are of this average diameter and such a correction is not to be ignored. Goldstein's function is a complicated one, but charts can be made out for applying the necessary corrections to Stokes' Law.

There are two more points worth mentioning, but these are not particular to this experiment and are to be considered generally in the theory of sedimentation. These are known as the ' wall-effect ' and the 'mutual influence' of particles on sedimentation. It is relevant to mention it here because in the Kennedy siltometer about 650 grammes of silt are thrown into a tube about 4 " diameter and are collected at the bottom in

a tube 1½ inches in diameter. Stokes' Law does not hold good in such a case. Of course 35 years ago, it might have been considered as an approximation, but with the development of Science and Engineering old things have to be discarded, though they may have an important place in the history of the development of the Science. A small amount of silt and a large tube should be used to ensure accuracy. There are wide limits between which these corrections are negligible and we have carried out experiments with tubes 1½ inches and 3 inches diameter with different amounts of silt. The Optical Lever Siltometer requires a very small amount of silt and it is not necessary to consider the errors arising out of these factors.

The shape factor of the silt is also to be considered at least qualitatively. Photographic study of the shape attached to each distribution curve will serve as useful appendix in many silt problems. We expect in a few months to get the apparatus to enable this to be done.

Conclusion.

The apparatus may also be used for studying the size distribution of soils, the rate of evaporation of water from a surface, etc., but it is not within our scope to go into the details of the experimental procedure in the various cases. The main object of the investigation has been to find a method, convenient and practicable for the analysis of silt within reasonable limits of accuracy and this appears to have been achieved as the foregoing results show.

In conclusion, I have great pleasure in thanking Dr. E. McKenzie Taylor, D. Sc., F. I. C., the Director of the Institute, for his keen interest in the problem. Much of the work and the labour involved in developing the apparatus would also have been impossible, but for the valuable help rendered to me by my assistant Mr. H. R. Luthra, M.Sc.

DISCUSSION.

The Author in introducing the paper said that he would explain the method of experimentation for the benefit of those to whom it might not be clear from the paper. He referred to figures (1), (2) and (3) on page 6 (an enlarged copy of which was put up on the board) and stated that the arrangement shown in Fig. 2 was fitted at D and the doors *d d* were closed and the requisite quantity of silt placed on it. The wire supporting the doors *dd* was then fused, dropping the silt just at the water surface. The spot of light at L_4 then went down due to the increase of pressure. The particles got graded according to Stokes' Law as they fell in water and when they passed the cross-section of the U tube of mercury the pressure was released and the spot began to move up. It would not go back to the original point due to the volume pressure.

The Speaker said that the above could be made clear by a reference to Fig. 4. DEFG was the most significant portion where most of the silt was falling. The time was indicated automatically by intercepting the light at known intervals by a rotating wheel. The last figure on the same page indicated the time spots. The white spots indicated intervals of 1/5 second. From known time and Stokes' Law the distribution curves shown in Figs. 5 and 7 were obtained, as explained in the theory.

Another point of importance to which the speaker drew attention was that Stokes' Law was not applicable for the average Punjab Silts when water was used as the sedimenting medium. Punjab silts were generally coarse and about 1/4 mm. average diameter. To obtain the correct diameter Oseens' Function must be evaluated for the corresponding Reynolds' numbers. This was a complicated function but charts could be made out and the corrections were illustrated in the second line along the horizontal axis. This had been ignored in the past.

By another set of curves on the board, the speaker also illustrated how the siltometer results were checked by the microscope.

Another point of interest to which he drew the attention of the audience was the exciting fact that in the Lower Bari Doab Canal which drew the water from two sources the silt curves were not smooth but drawn out. One could say from the laboratory that Lower Bari Doab Canal had two sources from which it took the silt.

The speaker expressed his regret that he could not demonstrate these facts as the hall could not be darkened and also due to experimental difficulties the working of the apparatus could not be demonstrated to the audience.

With a few more points as to the object of silt analysis, the speaker concluded his introduction thanking the Chair and the audience.

Dr. N. K. Bose said that he congratulated the author on his success in evolving a neat apparatus for silt analysis by combining the mechanical device of Shrader and Ryder with the principal ideas of Weigner. Dr. Weigner in Germany as early as 1918 first conceived the idea of utilising in the mechanical analysis of soil the hydrostatic fact that a body moving in a fluid medium exerted an extra pressure on the bottom of the vessel containing the fluid which was equivalent to the weight of the body in the fluid. In 1919 Messrs. Shrader and Ryder in America perfected an optical lever manometer by which movements of mercury as small as 1-1000th part of a millimeter could be detected. In 1932 those two things have been combined in the hands of the author and a neat siltometer was the result. It had got all the sensitiveness of Shrader's apparatus with the fineness of Weigner's Theory.

Talking of theory, Dr. Bose said that he must point out that the method of dropping the sample was first introduced in Weigner's apparatus in the Institute. Weigner, and for the matter of that all soil Physicists such as Keen, Oden and others have taken a soil solution and poured it into the siltometer tube. It introduced a state of turbulence in the tube in which it was not possible even for modern mathematics to calculate the rate of fall of any particle. To apply Stokes' Law to find the rate of fall of a sphere in a viscous medium, the first essential condition was that the medium should be motionless and the passage of the sphere should not leave a wake of turbulence. If this should occur, as it did when the diameter of the sphere approached the value 0.04 cm., Stokes' Law failed to account for its movement, and Oseen's Law, an exact solution of which had been recently obtained by Goldstein, held the field.

About the probable source of error of the siltometer Dr. Bose quoted from Shrader's paper in the Physical Review. The only source of error which need be considered was due to the adhesion of mercury to the walls of the tube, the deflection being therefore less than the actual value. If the mercury was very clean and the glass in good condition a large mercury surface from 5 cm., to 10 cm., should be used.

The President remarked that Dr. Bose and Dr. Vaidhianathan were men who knew more about theories than the Engineers and he was very glad that through the instrumentality of the Research Laboratory these gentlemen had come to their rescue. They awaited with eagerness the results which the labours of these gentlemen would bring to the Irrigation Department and to the Province.

He congratulated Dr. Vaidhianathan on his paper.

CORRESPONDENCE.

Mr. Gerald Lacey remarked that the author was to be congratulated on his very interesting paper and the very clever scientific device which he had described. As one who had been privileged to see it working he was unstinting in his admiration for it. The fact that so small

a sample of silt was necessary for experiment was a very practical advantage to those who possessed no apparatus but desired to send samples for test.

It was not stated in the paper whether the samples of silt taken from the Nasrana Distributary and its water-course were obtained from the bed. That was of importance because, he personally held the opinion that it was on the average diameter of the particles in contact with the bed at any instant, however difficult that diameter might be to assess or determine, that the rugosity, and hence all the hydraulic dimensions associated with the regime channel, such as velocity, hydraulic mean depth, and water surface slope depended.

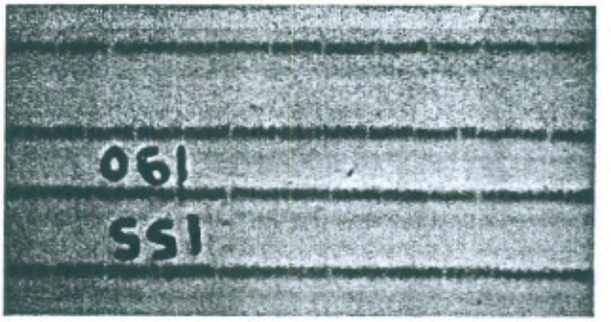
The density of the silt had not been mentioned. From a study he had made of figures from a great variety of sources, the density of ordinary silt sand, composed largely of quartz was remarkably constant at 2.65 or near that figure, extreme variations being about 2.55 and 2.75 respectively. Since density was variable the fact that the variations was small was of value.

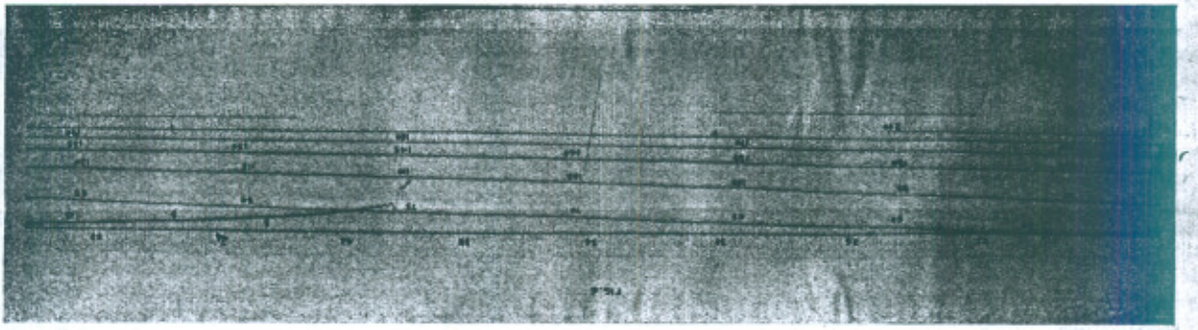
Time would show whether the mass of size distribution curves obtained from the beds of channels showed great variations in characteristics. If there were no great variation it would be much easier to determine what for want of a better term could be called the "average diameter." The experiments which the Author would shortly carry out would also show whether shape, and the extent of shape variation, was a characteristic of all silts from the same alluvium irrespective of grade. If that were so the problem would be simplified. The Author would be able to state the effect on a size distribution curve of an artificial mix.

He hoped that in time it might prove possible to link up the effective diameter of the bed silt particles with his own somewhat elusive silt factor.

For this purpose it was essential to consider samples from the active bed and not suspended particles.

He had been afforded a number of opportunities of inspecting the apparatus from its first inception at the Research Laboratory and he was indebted to the Institute and to its Director for the courtesy which had been extended to him.


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155



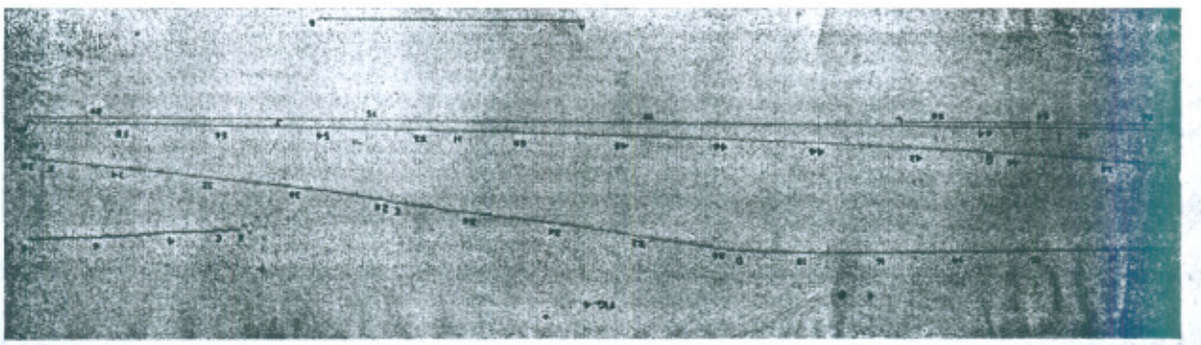


FIG. 5

SIZE DISTRIBUTION CURVE

No. OF SMALL SQUARES = 9256

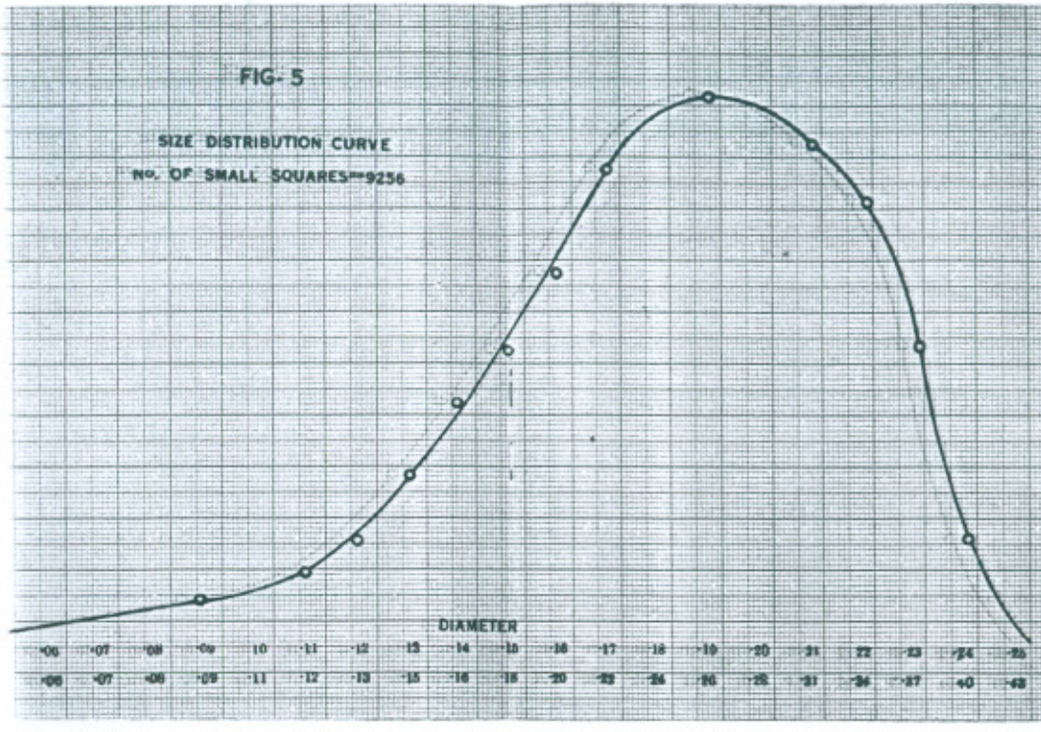


FIG. 7

SIZE DISTRIBUTION CURVE

No. OF SMALL SQUARES = 8033

