AN INSTRUMENT FOR RAPID SIZE-FREQUENCY ANALYSIS OF SEDIMENT

By

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In recent years one of the principal deterrents to more extensive sediment investigations has been the lack of a rapid and accurate method of size-frequency analysis of sediment. Sampling equipment and techniques have been perfected to such a point that thousands of sediment samples are obtained each year, but only a relatively few of these are analyzed for particle size-frequency distribution simply because present methods are too time consuming and costly. Many investigators have sought a solution to the problem with the result that a wide variety of ingenious devices and methods have been proposed. In a comprehensive study made jointly by the Iowa Institute of Hydraulic Research and six Federal agencies [1], the existing methods of analyzing sediment were evaluated and the requirements for suitable instrumentation were reviewed. This established a foundation for further work toward a rapid size-frequency analyzer. A bottom-withdrawal tube was proposed [1] and has gained wide acceptance. Unfortunately the bottom-withdrawal tube method is quite laborious and not suitable for rapid analysis.

From the extensive work that has been done on methods of size-frequency analysis, it is evident that the problems encountered are numerous and difficult. A successful instrument can be attained only after solutions are found to each of the problems involved. Important progress is being made at the Iowa Institute of Hydraulic Research on the development of a more rapid and accurate instrument. The three recent developments that will be discussed are as follows:

1. An improved method for producing stratified suspensions.
2. A method of making a differential pressure traverse of a stratified suspension which permits direct measurement of the size-frequency of the sediment.
3. An electrical pressure transducer for measurement of very

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small differential pressures such as are obtained in traversing stratified suspensions of sediment.

Following a discussion of these developments, their application in an experimental instrument now being tested will be described. Finally, the new technique of analysis will be compared with the widely used bottom-withdrawal method.

STRATIFIED SUSPENSIONS

Many of the methods that have been proposed for size-frequency analysis of sediments have been based on the theory of sedimentation from initially homogeneous suspensions, first published by Odén in 1915 [2]. In this method the sediment accumulating at the bottom of a column contains particles of all the sizes present in the sample. It is only by graphical analysis of the rate at which the sediment accumulates that the size frequency of the sediment can be determined. Other methods utilize stratified suspensions in which the sediment is separated according to its fall velocity, with the largest particles near the bottom of the column and the finest at the top. Two techniques have been used to obtain stratified suspensions. The first is to suspend the sediment in upward flow in a tapered column or series of columns of increasing diameter. This technique, called elutriation, permits only a rough separation of the different size particles because of the difficulties of establishing a constant upward velocity across the column, particularly if low velocities are required. The second means of producing a stratified suspension is to introduce the sediment at the top of the column of liquid. This has not been generally accepted because disturbances are caused by the introduction of the sample. Flocculation, induced eddy motion, and gravity currents prevent accurate separation of the particles according to their fall velocities.

The original work on an improved method of obtaining stratified suspensions was conducted at the State University of Iowa in 1948 by Col. H. J. Skidmore as a doctoral dissertation [3]. In this new method a filter is utilized which is sufficiently fine to support initially the sample of sediment at the top of the sedimentation column. As the filter is withdrawn the sediment is left to fall freely and thus to become stratified in the column. The main requirement for a suitable filter is a uniform porosity in order that there will be no eddy motion generated as the filter is withdrawn from the sediment. Skidmore used a loose-bed filter of lead shot and quartz sand. In

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the experimental results to be presented later it will be shown that this was used successfully. More recently the writer has used commercial porous metal filters made by the sintering of very fine metal beads. Difficulties encountered in the use of these are yet to be overcome, but it is hoped that they will eventually replace the loose-bed filter.

The use of a filter to obtain a uniform release of the sediment at the top of the column permits an important assumption to be made with acceptable accuracy: that all of the sediment begins its free fall from the initial elevation of the filter. This is justified provided that the depth of the sediment on the top of the filter is small compared to the total height of the sedimentation column, and provided that the filter is uniformly porous to eliminate eddy motion as it is withdrawn. The small-scale turbulence produced by the porous filter quickly decays without causing appreciable displacement of the particles in the suspension. Furthermore, the releasing of the entire sample at the top of the column causes the particles of different sizes to become separated quickly, thus minimizing interference between particles having different fall velocities.

The principal advantage in using a stratified suspension is that a direct indication of the size-frequency of the sediment can be obtained. The particles of sediment become arranged in the column according to their size so that the weight of sediment between any two levels at any time represents the amount of sediment in a particular size range. If the bottom-withdrawal technique were applied to a stratified suspension, the weight of sediment withdrawn at each interval would be the amount of sediment in the size ranges determined by the times at which the withdrawals are made. No graphical solution would be required for the size-frequency as is required by bottom-withdrawal from homogeneous suspensions. Time would be saved and the inaccuracy of the graphical solution eliminated. Furthermore, measurements of differential pressures in a stratified suspension can be made to obtain the weight of the sediment size fractions directly and thereby eliminate the task of drying and weighing each separately. These simplifications eliminate a large percentage of the work involved in other methods of size-frequency analysis. Thus, to be able to produce satisfactory stratified suspensions is an important step toward the achieving of rapid analyses of sediment.

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USE OF A DIFFERENTIAL-PRESSURE TRAVERSE

It was evident when the use of a stratified suspension was first being considered that a very simple measurement of differential pressures would give a direct indication of the weight of the individual sediment size fractions. The principle is illustrated in Fig. 1, which shows two piezometers in the wall of the sedimentation column connected to a differential pressure gage.

If the water in the sedimentation column contains no sediment,

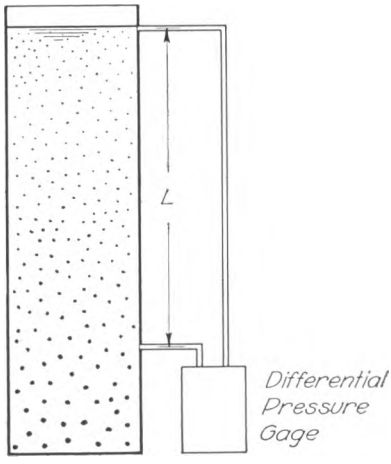

FIG. 1. PRESSURE-GAGE ARRANGEMENT FOR DETERMINING THE WEIGHT OF SUSPENDED SEDIMENT.

the differential pressure at the gage is zero. Introduction of sediment increases the effective density in the column and raises the pressure at the lower piezometer. The product of the differential pressure at the gage and the area of the sedimentation column must be equal to the submerged weight of the sediment in suspension between the piezometers. An equation for the differential pressure Δp is then

$$\Delta p = \frac{\gamma_s - \gamma_w}{\gamma_s A} \cdot W_s$$

in which

γ_s = specific weight of the sediment,
γ_w = specific weight of the water,
A = area of the sedimentation column, and
W_s = the total weight of sediment between piezometers.

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For a sedimentation column of area A, and for known unit weights of the sediment and water, the first term on the right is a constant, so that Δp is proportional to the total weight of sediment between the piezometers. Thus, if a sample of sediment is allowed to fall freely from the top of a sedimentation column, a differential pressure gage such as that shown in Fig. 1 indicates first the total weight of the sample, and then, as the coarser particles pass the lower piezometer, the weight of successively finer size-fractions.

A record of Δp versus time for a hypothetical river sediment is shown in Fig. 2. In this example the lower piezometer was located

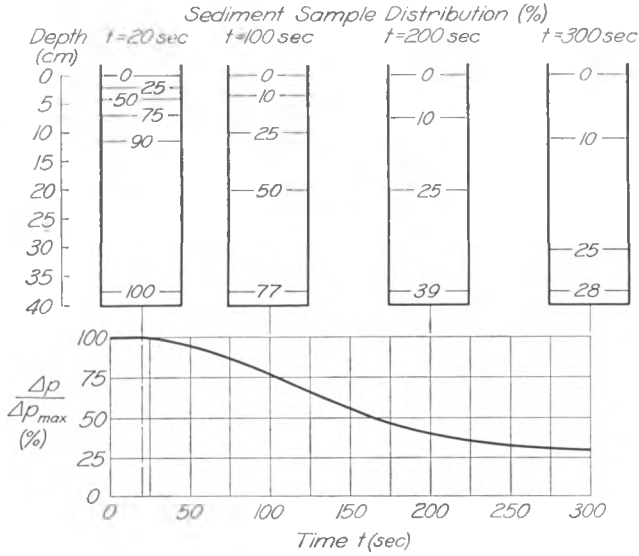

FIG. 2. DIFFERENTIAL PRESSURE RECORD DURING SEDIMENTATION OF TYPICAL RIVER SEDIMENT IN COLUMN WITH FIXED PIEZOMETERS 38 CM. APART.

arbitrarily 38 cm below the free surface. It can be seen that the time during which all of the sediment is in suspension between the piezometers is relatively short (20 seconds), yet after 300 seconds (five minutes) over a quarter of the sediment is still in suspension. It would take a long time for all of the sediment, or even 90 or 95 percent of it to pass the lower piezometer. To attain a rapid analysis, Skidmore made the lower piezometer traverse the sediment suspension so that during the analysis the length of column between the two piezometers could be reduced to zero. The resulting relationship

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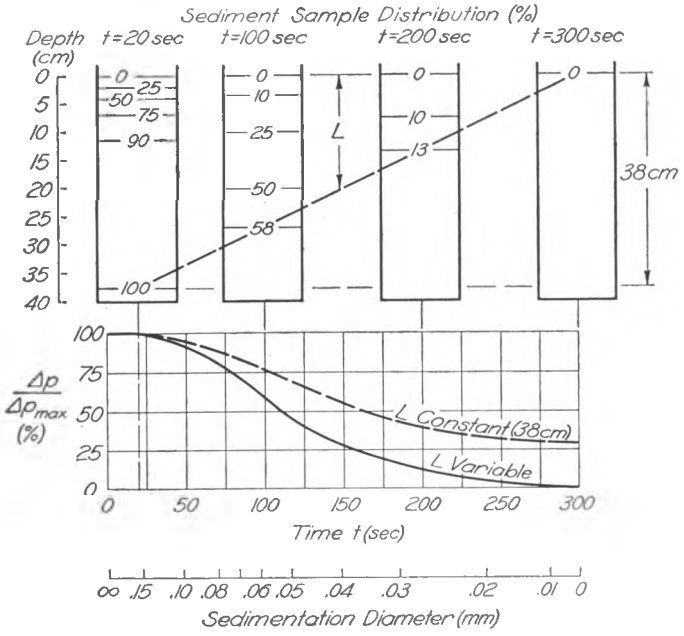

FIG. 3. DIFFERENTIAL PRESSURE RECORD DURING SEDIMENTATION OF TYPICAL RIVER SEDIMENT IN COLUMN HAVING TRAVERSING PIEZOMETER.

between Δp and time is shown in Fig. 3 for the case in which the elevation of the lower piezometer is increased at a constant rate. One of the most important advantages of this is that the total time for the test is reduced. The large particles still fall the full length of the column as before, the smaller particles fall just part way, and finally the next to the smallest particles of interest fall only as far as is necessary for them to become distinct from the smallest particles. The latter requirement governs the rate at which the piezometer can traverse the sediment suspension. For example, if the smallest particle size of interest has a fall velocity of 0.003 cm per second, and it must fall about 1 cm to become separate from finer particles, then the total time for the test would have to be about 300 seconds or 5 minutes. Further experiments will be required before the minimum fall that will be required for separation of the finest fraction can be determined.

The traversing of the sedimentation column at a constant rate has the additional advantage that an auxiliary scale of fall velocity or

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sedimentation diameter can be printed along the time axis as shown in Fig. 3. The plot is actually the conventional size-frequency distribution graph, except that the sedimentation diameter is not the usual logarithmic scale. Thus, the use of a stratified suspension and a constant-speed traverse yields a differential pressure record that can be plotted versus time to give directly the size-frequency distribution curve of the sediment.

A very sensitive liquid manometer was used in the Skidmore instrument to measure the differential pressure. It had the disadvantage that the traverse had to be stopped for readings to be taken. Also, it required a second operator and the recording of the numerical data before the results could be plotted. Skidmore suggested that the work involved in this phase of the analysis could be greatly reduced if an electrical pressure transducer and a pen recorder were used to give the size-frequency distribution curve automatically. The development of this equipment constitutes the third step toward the achievement of a satisfactory instrument for rapid sediment analysis.

AN ELECTRICAL PRESSURE TRANSDUCER

The development of electrical instruments for measurements of pressure has received considerable attention at the Institute since 1945. One objective has been to obtain a transducer for automatically recording slowly varying differential pressures of very small magnitude, such as might be obtained in sediment analysis. Re-

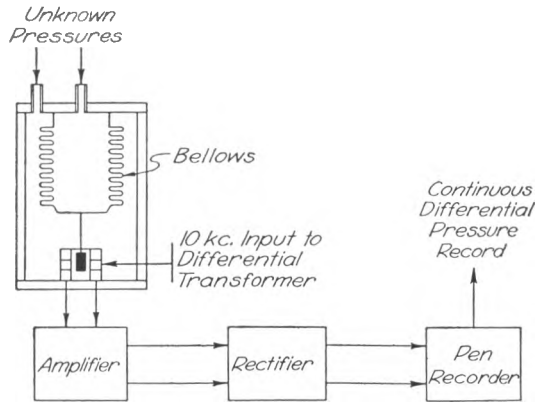

FIG. 4. SCHEMATIC DIAGRAM OF DIFFERENTIAL PRESSURE TRANSDUCER AND RECORDING EQUIPMENT.

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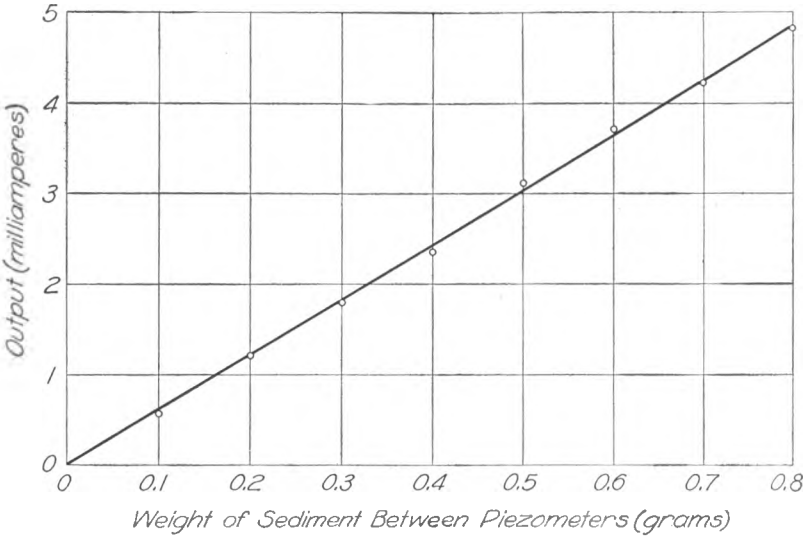

FIG. 5. CALIBRATION OF DIFFERENTIAL-PRESSURE TRANSDUCER.

cently a very simple instrument was constructed under the direction of Philip Hubbard of the Institute staff and was found to have the required sensitivity. A schematic diagram of the equipment is shown in Fig. 4. The unknown pressures are transmitted to closed chambers separated by a highly flexible metal bellows 2.5 inches in diameter. The twelve convolutions of the bellows allow the free end to deflect a measurable amount in response to minute differences in pressure. The bellows is attached to the movable core of a commercial differential transformer. Any movement of the bellows causes the core to be displaced, and the voltage in the two secondaries to become unbalanced. The difference between these voltages, after being amplified and rectified, activates a pen recorder. Both the bellows and the differential transformer have linear characteristics within their operating ranges. As a result, the displacement of the recording pen is directly proportional to the difference in the unknown pressures.

The sensitivity obtained in this instrument is unusually high as is indicated by the calibration curve shown in Fig. 5. Full-scale reading on the recorder can be obtained with less than one gram of sediment in the sedimentation column. This corresponds to a maximum differential pressure of less than 10^{-3} psi at the transducer, or, in terms of the usual differential water manometer read-

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ings, a maximum difference in liquid level of less than 0.0025 inch. The minimum reading on the recorder would then correspond to about 10^{-5} psi differential pressure or one one-hundredth of a gram of sediment. The corresponding movement of the bellows is also small, amounting to 0.0005 inch for full-scale output at the recorder, or a minimum observable displacement of about 5×10^{-6} inch. A sufficiently rapid time response is also obtained; Fig. 6 is a record of the response to an instantaneous change in differential pressure of the transducer connected to the two piezometers in the sediment columns. From this it can be seen that the time for essentially complete response of the transducer is about 3 seconds. It is axiomatic that there must be close control of extraneous variables for measurements of such small quantities to be made accurately. The variables having the greatest effect on the transducer indication are mean pressure, temperature, acceleration of part of the system, and air content. The provisions for controlling these are described in the discussion of an experimental instrument.

INSTRUMENT DESIGN AND OPERATION

The three new developments that have just been discussed have been incorporated into the design of an experimental instrument now being tested at the Institute. Although this work is being done by the writer as an Institute project as well as for his doctoral dissertation, it should be emphasized that the basic principles of the method and the first experimental equipment were the work of Col. Skidmore. A new design has been made to accommodate the use of

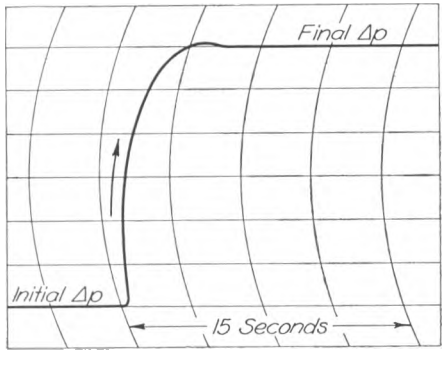

FIG. 6. RECORDED RESPONSE OF INSTRUMENT TO INSTANTANEOUS CHANGE OF DIFFERENTIAL PRESSURE IN THE SEDIMENTATION COLUMN.

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the electrical pressure transducer, and to make possible a continuous pressure traverse.

The arrangement of the sedimentation column, filter piston, piezometers, pressure lines and differential pressure transducer is shown schematically in Fig. 7. The sedimentation column and the pressure transducer are stationary, the pressure traverse being made by means of the traversing tube in the sediment column. The mean pres-

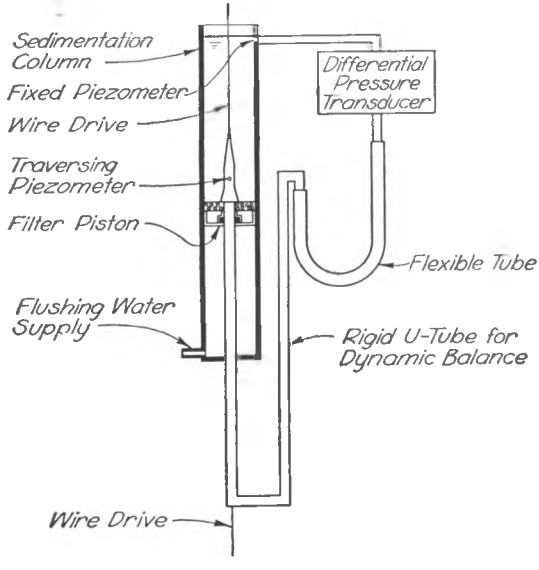

FIG. 7. SCHEMATIC DIAGRAM OF SEDIMENT ANALYZER.

sure at the transducer is, therefore, practically constant. The small changes that do occur do not appreciably affect the output of the transducer. The rigid brass U-tube between the traverse piezometer and the flexible tube to the transducer provides approximate dynamic balance in the pressure system; that is, a continuous traverse of the column can be made without the motion influencing the differential pressure indication. In the operation of the analyzer the filter is initially at the top of the column. The sediment sample is introduced along with a small volume of water in which the sample is dispersed; then the piston is withdrawn rapidly enough to keep ahead of the fastest falling particles of sediment. Gaskets between the filter piston and the column wall force the water in the column to pass upward through the filter. When the piston reaches the bottom of the column, it is stopped and the piezometer rod started

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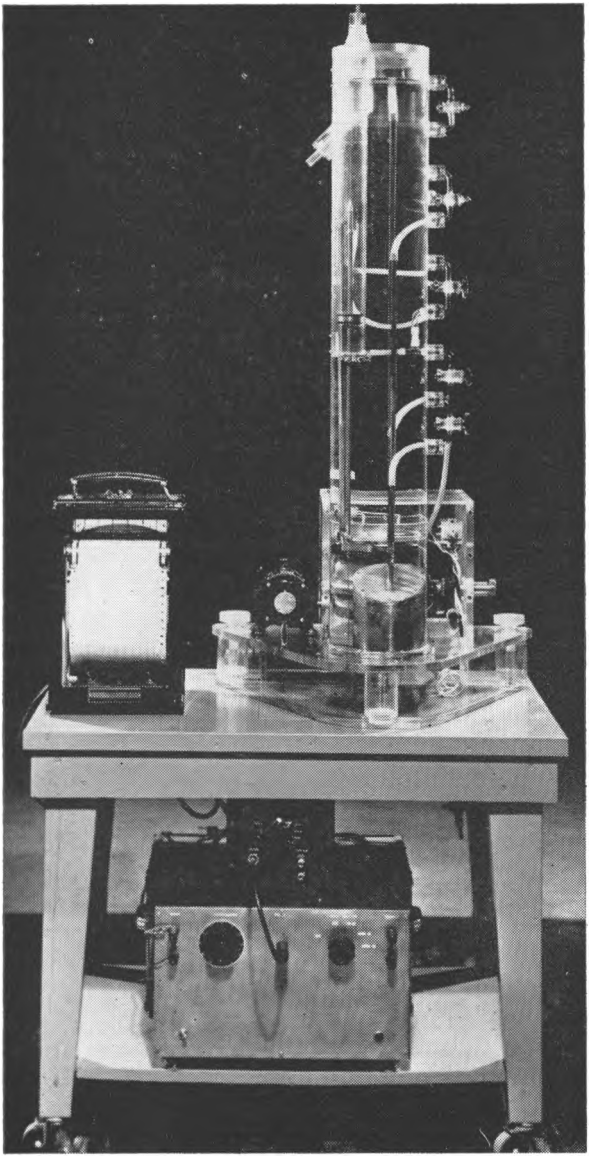

FIG. 8. APPARATUS FOR RAPID SIZE-FREQUENCY ANALYSIS OF SEDIMENT.

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slowly back up through the column. The filter is held in place by friction while the piezometer rod slides smoothly upward through a small O-ring gasket. At the end of this traverse, during which the differential pressure record has been obtained, the sediment is flushed out and the filter returned to the top of the column by water which is admitted under pressure at the bottom of the column. Finally, a small amount of water is drained from the column to bring the water surface down to the level of the upper piezometer and to make room for the next sample to be introduced.

This experimental instrument for size-frequency analysis is shown in Fig. 8. A large plastic cylinder filled with water contains as much of the equipment as is feasible so that a constant temperature can be maintained. The pressure transducer is in the bottom of the water bath and is connected to the sedimentation column through valves mounted on the plastic cylinder. These valves permit the transducer to be isolated, the pressure lines to be flushed to remove air, and the sedimentation column to be flushed to remove the sediment at the end of a test. The synchronous motor and gear-change mechanism which are used for driving the piston and piezometer on their traverses are behind the water bath. To the left is the pen recorder and below the electronic amplifier. In addition to the equipment shown, there must be an A-C power supply and a reservoir of water

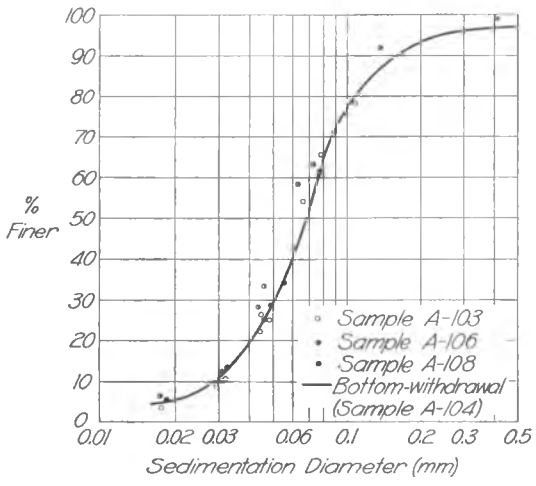

FIG. 9. COMPARISON OF RESULTS FROM SKIDMORE'S APPARATUS AND THE BOTTOM-WITHDRAWAL TUBE.

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kept at the same temperature as the water in the constant-temperature bath.

COMPARISON WITH BOTTOM-WITHDRAWAL METHOD

The instrument just described has been at its present stage of development such a short time that no analyses have been run for comparison with other methods. However, the principles have already been checked by Skidmore with his experimental apparatus and comparative analyses run with the bottom-withdrawal tube. The results were presented in Skidmore's dissertation, in which he concluded that "the results obtained do show good agreement with results obtained by bottom-withdrawal methods except that, in general, particle sizes given by the experimental apparatus tend to exceed those obtained by bottom-withdrawal methods, particularly in the upper size brackets." Some of the results on which this conclusion was based are shown in Fig. 9. The bottom-withdrawal method of analysis was used as the basis for the comparison because it had been checked by the pipette method, and because it had become widely recognized and accepted.

There are other factors that should be considered in a comparison of the two methods for size-frequency analysis. One is that the experimental analyzer is more complex than the bottom-withdrawal tube. However, the difference is perhaps not as great as it may first appear to be. For example, the electronic components in the experimental analyzer are standard commercial instruments which are easy to use and seldom need servicing. These are comparable, in a way, to the auxiliary equipment necessary for bottom-withdrawal analysis: the Gooch crucibles, vacuum filters, drying oven, and analytical balance. The electronic equipment in effect replaces these, speeding up the process of "weighing" the sediment fractions. Since the electronic instruments and the analyzer itself are relatively simple to use, no special skill or training would be required of an operator. The human element is minimized by the use of the automatic equipment and by the elimination of the graphical solution required in the bottom-withdrawal method.

The principal advantage of the new method is the reduction in the time required to analyze each sediment sample. It has been estimated that a technician can run about 4 to 6 complete size-frequency analyses in an eight-hour day by the bottom-withdrawal method. This includes the operating of the withdrawal tube, the filtering,

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the drying and weighing of the sediment, and the calculating and plotting of the results. The same number of samples could be run in less than an hour by the new method. About four minutes would be required to run the analysis of each sample, and probably about the same length of time to flush the sample from the column and to introduce the next. This would increase the number of samples that a technician could run in a day to about ten times the number possible by using the bottom-withdrawal method.

There is one additional advantage that should be noted. It has been known for a long time that the presence of numerous falling particles in a column of liquid would probably have an effect on the fall velocities of the individual particles. Now both theoretical and experimental evaluations of the concentration effect on fall velocity have been made and brought to the attention of the profession by McNown and Lin [4]. For statistically homogeneous concentrations as low as 1000 parts per million surprisingly large reductions in velocity — 10% — were recorded. For higher concentrations the reduction in velocity was found to be even greater. Corrections for the concentration effect can be applied to the size-frequency results obtained from stratified suspensions, whereas they cannot from homogeneous suspensions. Thus, the new instrument holds promise not only for more rapid but also for more precise measurements of sediment size-frequency than can be made with other instruments now available.

DISCUSSION

Mr. Barbarossa remarked that any step directed toward improvement of field instrumentation in sedimentation is a very worthy endeavor. Mr. Appel's efforts to develop the instrument he described for the purpose of expediting one of the important phases of sediment investigations are very commendable. The question could be raised as to whether or not stratification in the sediment tube actually occurs. However, the instrument is acceptable to the field engineer because the indications to date are that the results yielded by Mr. Appel's instrument are at least as good as those obtained by means of the bottom-withdrawal tube, which has been rather generally accepted.

Much river data on sediment has been collected in the past for limited purposes. It is very rare indeed that river data are obtained for the far-sighted purpose of contributing to a total solution of

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the sediment transport problem. Yet the gathering of complete and reliable river data for this purpose seems to be a very urgent need. An extremely serious obstacle to the collection of stream data for this aim is the lack of instrumentation which yields reliable results at low cost. Making both hydraulic and sediment measurements in the field with the instruments available at present is very time-consuming and, hence, costly. For this reason those who control the purse strings of sediment investigations are inclined to discourage, if not to forbid, investigations which involve more than a piecemeal attack upon a pressing local problem.

There are several existing theories of sediment transport, concerning which there is much disagreement and confusion. The engineering profession will not accept these theories, and justly so, until it has been demonstrated that they actually do predict, within reasonable limits, sediment behavior in both natural and artificial streams. At present no such substantiation exists. Doubt as to the validity of existing theories is raised because, primarily, these theories are based upon the results of laboratory experiments and observations. In many hydraulic problems there is no bar to complete acceptance of laboratory results. Unfortunately, in the case of sediment transport the applicability of flume results is severely restricted. It is extremely difficult, if not impossible, to evaluate the behavior of sediment in natural streams from laboratory studies alone. Neither does it appear possible to arrive at a complete theory of sediment transport from a study of river measurements alone. The laboratory specialist and the field specialist must each look to the other for guidance.

Mr. Mitchell thought that the instrument as designed was primarily for silts and clays and asked if it might be extended to include sands as well.

Mr. Bondurant also thought that the instrument should, if possible, be extended into the sand range.

Mr. Albertson indicated that in most streams the flow is turbulent, so that the particles are given very erratic motions and may tend to settle in some manner other than that under controlled conditions in an instrument such as Mr. Appel described. The effects of particle orientation might be a factor.

Mr. Johnson questioned the sign of the effect of concentration on the fall velocity. Mr. McNown replied that experiments in the In-

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stitute indicated that the fall velocity decreased with increase in concentration.

Mr. Feodoroff suggested the use of varicolored particles and moving pictures to determine actual size distribution as a standard for comparison.

In reply to Mr. Mitchell, Mr. Appel said that the instrument as now constructed was principally for use in the silt range. More experience with the operation of the instrument will be needed before indicating its applicability to sands and clays. However, for the analysis of sands a much simpler arrangement should be possible. Because of the relatively high fall velocities of sands, it should be possible to obtain satisfactory stratified suspensions by introducing the samples at the top of the sedimentation column without using the filter. The traversing mechanism and operation would be simplified, but the automatically recorded graph of the size-frequency distribution would still be obtained.

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Bulletin 18. "Percolation and Capillary Movements of Water Through Sand Prisms," by F. T. Mavis and Tsung-Pei Tsui, 1939. 32 pages, 13 figures, price $0.25.

Bulletin 19. "Two Decades of Hydraulics at the University of Iowa, Abstracts of Theses, Publications, and Research Reports, 1919-1938," edited by F. T. Mavis, 1939. 84 pages, price $0.50.

Bulletin 20. "Proceedings of Hydraulics Conference," edited by J. W. Howe, 1940. 260 pages, 84 figures. Out of print.

Bulletin 21. "Studies of One and Two-Handed Work," by Ralph M. Barnes, Marvin E. Mundel, and John M. MacKenzie, 1940. 68 pages, 31 figures, price $0.50.

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Bulletin 29. "Study of Transportation of Fine Sediments by Flowing Water," by A. A. Kalinske and C. H. Hsia, 1945. 40 pages, 18 figures, price $0.40.

Bulletin 30. "The Iowa Institute of Hydraulic Research," 1946. 80 pages, 36 figures, price $0.50.

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Bulletin 33. "Third Decade of Hydraulics at the State University of Iowa," edited by M. C. Boyer, 1949. 84 pages, 8 figures, price $0.50.

Bulletin 34. "Proceedings of the Fifth Hydraulics Conference," edited by John S. McNown and M. C. Boyer, 1953, 302 pages, 139 figures, price $3.50.

http://ir.uiowa.edu/uisie/34

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Institute articles which have appeared since publication of Bulletin 33 in 1949

79. "Pressure Distributions from Theoretical Approximations of the Flow Pattern," by John S. McNown and En-Yun Hsu; *Heat Transfer and Fluid Mechanics Institute 1949*, pp. 65-76, published by the A.S.M.E. Price $0.25.

81. "Influence of Boundary Proximity on the Drag of Spheres," by J. S. McNown, H. M. Lee, M. B. McPherson, and S. M. Engez; *Proc. of the VII International Congress for Applied Mechanics*, pp. 17-29, London 1948. Price $0.30.

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83. "Characteristics of Irrotational Flow through Axially Symmetric Orifices," by Hunter Rouse and Abdel-Hadi Abul-Fetouh; *Journal of Applied Mechanics*, Vol. 17, No. 4, pp. 421-426, 1950. Price $0.10.

84. "How the Vortex Affects Orifice Discharge," by C. J. Posey and Hsieh-Ching Hsu; *Eng. News-Rec.*, Vol. 144, No. 10, p. 30, March 9, 1950. Price $0.05.

85. "Effects of Particle Shape on Settling Velocity at Low Reynolds Numbers," by John S. McNown and Jamil Malaika; *Trans. A.G.U.*, Vol. 31, pp. 74-82, 1950. Price $0.15.

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94. "An Investigation of Flow through Screens," by W. D. Baines and E. G. Peterson; *Trans. A.S.M.E.*, Vol. 73, p. 467, 1951. Price $0.15.

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96. "Application of Conformal Mapping to Divided Flow," by John S.

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